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REVIEW AND EVALUATION  
OF  
NATIONAL AIRSPACE SYSTEM MODELS

A.R. Odoni  
R.W. Simpson

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NATIONAL AIRSPACE SYSTEM MODELS

OCTOBER 1979

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16. Abstract This report is intended to serve as a guide to the availability and capability of state-of-the-art analytical and simulation models of the National Airspace System (NAS). An extensive literature search produced a listing of 230 reports potentially containing technical descriptions of models developed during the last decade. These reports are classified into primary categories based on applicability of the model to various aspects of the NAS. Capacity/delay models are classified as capacity-oriented runway, delay-oriented runway, complete airport, terminal airspace, air route traffic (including communications), controller workload and performance, and models of major segments of the NAS. Reports describing models primarily concerned with safety-related measures and noise-related measures are categorized separately. Reports were initially screened to eliminate those known to have been superseded by a subsequent report, and those containing inadequate or inconsequential technical information concerning models. The remaining reports (approximately 180) were subjected to a detailed review. The results of this review are documented for each of the 50 distinct models described by the selected reports. Information contained in each model review includes report ID, abstract, input/output parameters, computer-related characteristics, assumptions, quality of documentation, extent of validation, and an evaluation of the model's usefulness and limitations. Another part of the report contains a comparative evaluation of models in the same primary category. These evaluations present an overview of the models contained in each category, summarize the main features of the best models, and document the conclusions and recommendations regarding the models best suited for specific applications.					
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## PREFACE

This report is the end result of work performed at the Flight Transportation Laboratory of M.I.T. under contract with the U.S. Department of Transportation/Transportation Systems Center. The authors would like to acknowledge the assistance of John D. Pararas, a graduate student and research assistant at the Laboratory, in reviewing models of Terminal Airspace (Category A4). Ms. Rebecca Lacy, the Laboratory's former librarian, was responsible for the initial collection and cataloging of many of the documents that were reviewed in the course of the work.

The authors were most fortunate to have Mr. Frederick Frankel of the Transportation Systems Center as DOT Technical Monitor of the study. Throughout the project he used the right combination of encouragement and prodding to see it to its conclusion according to schedule. He offered valuable suggestions and criticism during all stages of the work. His meticulous editing of the first draft of this report contributed greatly to the readability of the final version.

The authors would also like to acknowledge Ralph Kodis of the Transportation Systems Center for helpful comments in a number of meetings at TSC.

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# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

Symbol When You Know Multiply by To Find Symbol

### LENGTH

in	inches	2.5	cm	centimeters
ft	feet	30	m	meters
yd	yards	0.9	m	meters
mi	miles	1.6	km	kilometers

### AREA

in <sup>2</sup>	square inches	6.5	cm <sup>2</sup>	square centimeters
ft <sup>2</sup>	square feet	0.09	m <sup>2</sup>	square meters
yd <sup>2</sup>	square yards	0.8	m <sup>2</sup>	square meters
mi <sup>2</sup>	square miles	2.6	km <sup>2</sup>	square kilometers
acres	acres	0.4	ha	hectares

### MASS (weight)

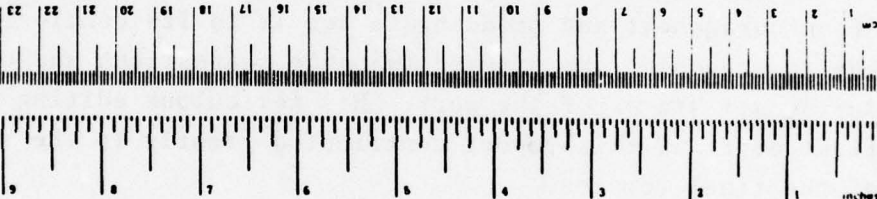
oz	ounces	28	g	grams
lb	pounds	0.45	kg	kilograms
	short tons (2000 lb)	0.9	t	tonnes

### VOLUME

teaspoon	teaspoons	5	ml	milliliters
tablespoon	tablespoons	15	ml	milliliters
fluid ounce	fluid ounces	30	ml	milliliters
cup	cups	0.24	l	liters
pint	pints	0.47	l	liters
quart	quarts	0.95	l	liters
gallon	gallons	3.8	l	liters
cubic foot	cubic feet	0.03	m <sup>3</sup>	cubic meters
cubic yard	cubic yards	0.76	m <sup>3</sup>	cubic meters

### TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	°C	Celsius temperature
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## Approximate Conversions from Metric Measures

Symbol When You Know Multiply by To Find Symbol

### LENGTH

mm	millimeters	0.04	in	inches
cm	centimeters	0.4	in	inches
m	meters	3.3	ft	feet
m	meters	1.1	yd	yards
km	kilometers	0.6	mi	miles

### AREA

cm <sup>2</sup>	square centimeters	0.16	in <sup>2</sup>	square inches
m <sup>2</sup>	square meters	1.2	yd <sup>2</sup>	square yards
km <sup>2</sup>	square kilometers	0.4	mi <sup>2</sup>	square miles
ha	hectares (10,000 m <sup>2</sup> )	2.5	acres	acres

### MASS (weight)

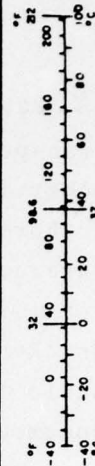
g	grams	0.035	oz	ounces
kg	kilograms	2.2	lb	pounds
t	tonnes (1000 kg)	1.1		short tons

### VOLUME

ml	milliliters	0.03	fl oz	fluid ounces
l	liters	2.1	pt	pints
l	liters	1.06	qt	quarts
l	liters	0.26	gal	gallons
m <sup>3</sup>	cubic meters	35	cu ft	cubic feet
m <sup>3</sup>	cubic meters	1.3	cu yd	cubic yards

### TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	°F	Fahrenheit temperature
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## LIST OF ABBREVIATIONS

ARTCC: Air Route Traffic Control Center  
ASDE: Airport Surface Detection Equipment  
ASR : Airport Surveillance Radar  
ATA : Air Transport Association  
ATC : Air Traffic Control  
ATCRBS: Air Traffic Control Radar Beacon System  
CAS: Collision Avoidance System  
CATER: Collection and Analysis of Terminal Records  
CNEL: Community Noise Equivalent Level  
CTOL: Conventional Takeoff and Landing  
DABS: Discrete Address Beacon System  
DME: Distance Measuring Equipment  
EPNL: Effective Perceived Noise Level  
FAA: Federal Aviation Administration  
ICAO: International Civil Aviation Organization  
IFR: Instrument Flight Rules  
ILS: Instrument Landing System  
Ldn: Day Night Average Sound Level  
Leq: Equivalent Sound Level  
MLS: Microwave Landing System  
NAFEC: National Aviation Facilities Experimental Center  
NAS: National Airspace System  
NASA: National Aeronautics and Space Administration  
NEF: Noise Exposure Forecast  
OM: Outer Marker  
PNL: Perceived Noise Level  
RNAV: Area Navigation  
SID: Standard Instrument Departure  
STAR: Standard Terminal Arrival Route  
STOL: Short Takeoff and Landing  
TSC: Transportation Systems Center  
VFR: Visual Flight Rules  
VOR: Very High Frequency Omnidirectional Range  
VTOL: Vertical Takeoff and Landing

PART I  
INTRODUCTION



## 1. SCOPE

The intent of this report is to provide air traffic control and airport specialists and planners with a convenient guide to state-of-the-art models pertaining to the National Airspace System (NAS). The term "model" is used here to denote a mathematical abstraction/representation of some aspect of NAS that, through manipulation, can provide insight regarding performance of current or proposed system configurations. Models can take the form of sets of mathematical relationships for which (closed-form or numerical) solutions are sought, or of fast-time, digital computer simulations. The former will be referred to here as "analytical models" and the latter as "simulation models." Both types of models are reviewed in this report.

Models reviewed are primarily those developed after 1970, although a small number of earlier models which are close to the state of the art today are also included. An earlier report\*, prepared at MIT, reviews many pre-1970 models of the National Airspace System.

Models have been classified into categories and are evaluated with respect to criteria which are explained in the following sections of Part I. The balance of the report contains comparative evaluations of the models in each category (Part II), and detailed reviews of each model (Part III).

It is hoped that this report will be a valuable tool for both those who wish to perform analyses with the aid of existing models and those who wish to develop new models. While not intended as a source of detailed descriptions of each model, this report should facilitate the process of identifying the most promising models and of gaining a good preliminary understanding of their capabilities and limitations.

\*Evaluation of Air Traffic Control Models and Simulations, Report No. DOT-TSC-FAA-71-7, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, June 1971.

## 2. CLASSIFICATION BY CATEGORIES

To enhance the readability and usefulness of the report, it was decided to arrange the models into a limited number of primary categories. Although many possible classification schemes can be conceived, it seems that the most obvious scheme is also the most informative. Accordingly, the models have been classified by subject matter, i.e. the aspect of National Airspace System operations with which they are primarily concerned. The following primary categories have been identified:

### Capacity/Delay Models

<u>Category</u>	<u>Applicability</u>
A1 <u>Capacity-oriented</u> models representing operations in the final approach/runway sequence (for landings), and on runways (for takeoffs), for various runway combinations and configurations, arrival/departure mixes, etc.	Runways
A2 <u>Delay-oriented</u> models representing operations in the final approach/runway sequence (for landings), and on runways (for takeoffs), for various runway combinations and configurations, arrival/departure mixes, etc.	Runways
A3    Models representing airport operations from final approach to apron gate, and back through completion of takeoff.	Complete Airport
A4    Models representing operations such as holding, vectoring, sequencing, metering and spacing in the terminal area.	Terminal Airspace
A5    Models representing ARTCC operations, airway flows, airway intersections, en route flow control, communications workload of sectors.	Air Route Traffic



<u>Category</u>		<u>Applicability</u>
A6	Models representing controller actions, used to estimate <u>controller workload and performance</u> under various operating conditions.	En Route Sectors
A7	Macroscopic models of all, or of major segments, of the National Airspace System (NAS) covering departure, en route, and arrival phases of flight.	Major Segments of NAS

#### Safety Models

B1	Models used to compute collision probabilities, deviations from prescribed flight paths, and other safety-related measures.	Various phases of flight
----	---	--------------------------

#### Noise Models

C1	Models used to compute noise-related measures.	Vicinity of airports
----	--	----------------------

It is clear, of course, that a particular model's coverage or usefulness may not be confined to a single one of the above categories. Thus, while a model is always assigned to a single primary category, that same model may also be cross-referenced as having applications in several other of the categories specified above. The Bibliography identifies those models which can also be associated with one or more secondary categories and specifies these categories, if any.

### 3. LITERATURE SEARCH

An extensive literature search has been conducted in connection with this project. Bibliographies compiled by several organizations were reviewed (see Exhibit I). The total number of reports referenced in these (already specialized) bibliographies

## EXHIBIT I

### SOURCES OF BIBLIOGRAPHIC INFORMATION

The following sources of bibliographic material on models/simulations related to aspects of the National Airspace System have been searched:

1. Civil Aviation Authority (United Kingdom), Acquisitions List. (Air Traffic Control, Air Transport) 1972-1977.
2. International Civil Aviation Organization, Air Traffic Control: A Selected List. (Covers reports acquired between 1970 and 1975.) Issued in 1975.
3. International Civil Aviation Organization, Acquisition Lists. (Air Traffic Control, Air Transportation, Air Navigation.) 1971-1977.
4. The MITRE Corporation, MITRE Bibliography on ATC Models and Simulations. Bibliographical search conducted especially for this project. February 1978.
5. National Aeronautics and Space Administration, Special Search on Airport Planning, NASA Literature Search No. 36032 (Special), August 4, 1977.
6. National Aeronautics and Space Administration, Special Search on Airport Planning, NASA Literature Search No. 36032 (Rerun-Special), August 8, 1977.
7. National Aeronautics and Space Administration, Air Traffic Control Models and Simulation, NASA Literature Search No. 37534, February 6, 1978.
8. National Aeronautics and Space Administration, Air Traffic Control Models and Simulations, Part II: Limited Distribution References, NASA Literature Search No. 37534, February 6, 1978.
9. National Technical Information Service, Air Traffic Control Simulation Models: A Bibliography with Abstracts. (Search period covered: 1964 - July 1977) Document NTIS/PS-76/0610.

10. National Technical Information Service, Air Traffic Congestion and Capacity: A Bibliography with Abstracts. (Search Period covered: 1964 - May 1977.) Document NTIS/PS-76/0495.
11. Transportation Research Board, Airports Bibliography, Report FAA-EM-77-15, October 1977.
12. Transportation Research Board, ATC Models and Simulations, Special Run for Flight Transportation Laboratory, Run No. A001049, February 1, 1978.
13. Transportation Systems Center, Bibliography of Technical Reports: July 1970 - December 1976, Report DOT-TSC-OST-77-17, April 1977.



is on the order of 2,500. The MITRE, NASA, and ATRIS bibliographies (items 4, 7, 8 and 12) were prepared especially for this project. On the basis of this literature search a list of "Reports of Interest" was prepared.

In most instances, the bibliographies of Exhibit I contain the abstracts of the reports they list. These abstracts were particularly valuable in determining a report's appropriateness, or lack thereof, for further consideration. When an abstract was not available, the title of the report (in addition to such information as authors, sponsoring organization, and keywords) was used as an indicator of the contents of the report.

For a report to be considered appropriate for inclusion in the list of "Reports of Interest," all of the following criteria must be satisfied.

- a. The date of publication of the report must be 1970 or later (A few earlier reports which may still constitute the state-of-the-art in some areas were excepted.)
- b. The title, abstract, or keywords must clearly indicate that the report contains the description of an analytical or simulation model related to one or more aspects of the National Airspace System.
- c. As far as can be inferred from title/abstract/keywords, the description in question is a truly technical one; i.e. the report does not, for instance, constitute advertising material for an organization, nor is it a purely qualitative discussion of what a model "might be" or "should be" like.
- d. The model is not concerned with optimizing the design of specific types of equipment, such as the Microwave Landing System or Collision Avoidance Systems. However, models for evaluating the need for, or the potential impact of, such equipment are admissible.

A "liberal" attitude was taken in those instances where it was not quite clear whether one or more of the above criteria were satisfied. That is, when in doubt as to whether a report was appropriate for inclusion in the list of "Reports of Interest," that report was included.

The "Reports of Interest" were subsequently classified into the various primary categories, resulting in the Bibliography presented in Appendix B containing 230 items.

#### 4. SELECTION OF REPORTS REVIEWED IN DETAIL

Not all of the reports listed in the Bibliography were reviewed in detail. The following criteria were used to identify the reports whose review was not necessary.

- i.) The report is a familiar one to the project team and is known to have been superseded by a subsequent report on the same topic (for instance, such a report might be an interim report on a model-development project and a subsequent final report has rendered the earlier report superfluous).
- ii.) The report is a familiar one to the project team and either does not describe a model in adequate detail or it contributes little to the state of the art in its area.
- iii.) The report is unknown to the project team but, for a variety of reasons, it appears highly unlikely that it contains the description of an important analytical or simulation model.

A total of about 180 reports were thus finally selected for detailed review. A substantial number (approximately 85) of these reports were found to be of limited value to this study for one or more of the following reasons: (1) does not describe a model (some contain analyses that make use of models described elsewhere); (2) model description is too superficial to permit a substantive evaluation; or (3) the model described is clearly superseded by another model in the same general area of application. Reports

falling into this category are listed as "Other Related Reports Read" in the bibliographical sections that accompany the comparative evaluations in Part II.

## 5. PRESENTATION OF MODEL REVIEWS

Part II of this report contains comparative evaluations of the models reviewed in each of the primary categories. These evaluations have not been written in a standard format due to the different nature of the models in the various categories. The comparative evaluations, as a rule, begin with an overview of the various models contained in each category, summarize the main features of the best models reviewed in that category, and present the principal conclusions that were drawn during the review process. Each primary category evaluation section also contains (1) a listing of models reviewed and supporting documents, (2) an indication of the attainability of the computer program for each model reviewed. (3) a listing of other related reports read and, (4) a listing of reports identified by the literature search but not reviewed for one or more of the reasons described in section 4 above. It is strongly recommended that the reader peruse the comparative evaluation for a primary category before reading the detailed reviews of models in that category.

The detailed model reviews, contained in Part III of the report, have been written according to a standard format consisting of eleven items. The following paragraphs describe the nature of the contents of each of the items.

Item 1: Primary Model Category. One of the nine primary model categories is selected as the one to which the model belongs.

Item 2: Report(s) Used to Evaluate the Model. For the report (or reports) describing the model this item lists: its title; author(s); agency or organization generating the report (this may be different from the sponsoring government agency, if any); report number; date; other identification information (such as NTIS number - when applicable - or sponsoring government agency and contract/grant number when applicable).



Item 3: Author's Abstract or Reviewer's Summary. If the abstract of the report describing the model provides an adequate brief description of the model, that abstract is included. Otherwise, a brief model summary is prepared by the evaluators.

Item 4: Model Description. This item consists of several subitems as follows:

4.1. Model Type: Classifies the report with regard to two descriptors: analytical vs. simulation; and deterministic vs. probabilistic.

4.2 Factors of National Airspace System Related to Model: Identifies the factors of the National Airspace System with which the model is most concerned.

4.3 Input Data Requirements: Identifies the most important inputs necessary to run/use the model.

4.4 Outputs Obtainable: Identifies the major outputs obtainable from the model.

Item 5: Computer-Related Characteristics. Indicates whether a computer program has been written to implement the model in question. If a computer program does exist, the following items are covered (whenever such information is available): computer language used; typical running times and/or costs for the program; amount of effort needed to prepare the inputs for computer runs.

Item 6: Major Assumptions. Lists the major assumptions of the model with remarks, when appropriate, on their reasonableness. Also notes aspects of real-world operations which are omitted by the model.

Item 7: Status of Model: Indicates, whenever this information is available, whether the model in question is being actively used at this time, whether further model development is in progress, etc.

Item 8: Quality of Documentation. Comments on the explicitness and clarity of the report in which the model is described. With regard to computer-implemented models, comments on software documentation such as flow-chart presentation, user's and programmer's guide, program listing, etc.

Item 9: Extent of Model Validation. Indicates if information is available on whether or not the model has been validated against data from the field. If this is the case then this item summarizes this information and comments on the extent to which the model can be considered "validated."

Item 10: Modularity and Flexibility. An indication as to how easily the model can be extended to include additional considerations, and suggestions for extensions of the model. Comments are also made on the possibility of combining the model in question with other available models to provide a tool of expanded scope.

Item 11: Summary Evaluation. Offers an appraisal of the value and usefulness of the model on an absolute basis and, if possible, by comparing it to other models in the same area. Specific strong and weak features of the model are usually listed in order to provide guidance and assistance to potential users of the models or to future researchers in this area. In addition, this item identifies the type of application for which the model in question is most appropriate.

PART II  
COMPARATIVE EVALUATIONS

## 1. CAPACITY-ORIENTED RUNWAY MODELS (CATEGORY A1)

Models in this category are concerned with providing estimates of hourly runway capacity, i.e. of the number of movements (landings and takeoffs) that can take place on a runway -- or on a combination of runways -- in an hour, under various conceivable sets of conditions.

A list of Category A1 models reviewed and supporting documents is contained in Section 1.6. Attainability of computer programs for the models in this category is indicated in Section 1.7.

### 1.1 DEFINITION OF "CAPACITY"

In introducing this section, it is important to devote some space to the question of capacity definitions, since this survey has discovered a marked shift in this respect from the concepts that were still dominant at the time of the 1971 Survey of ATC Models. Specifically, even as recently as 1971, it was still customary to define hourly runway capacity in terms of a standard of performance with regard to runway delays. In other words, runway capacity was defined as the number of movements that can be handled by the runway(s) over an hour such that average delay to aircraft using the runway(s) is equal to a specified threshold value. That value was usually taken to be equal to 4 minutes for airports with mostly commercial traffic, and to 2 minutes for airports serving primarily general aviation aircraft. This capacity came eventually to be known as the practical hourly capacity (PHCAP). The widespread use of PHCAP can be attributed to its adoption by the Airborne Instruments Laboratory's (AIL) Handbook of Airport Capacity (1, 2). The AIL Handbook was widely distributed and used during the 1960's and early 1970's but can be considered outdated now.

The PHCAP-type of capacity definition has been extensively criticized over the years. Its main shortcoming is that, by linking capacity to delay, it links in effect the capacity of an



airport to the time-pattern of demand at that airport. A brief hypothetical example will illustrate this point clearly: Suppose that the ATC separation rules and the traffic mix at a runway which is used only for landings are such that aircraft can land on this runway at intervals of exactly 2 minutes, or at a rate of 30 landings per hour. Let us also assume that the airline schedule is such that this runway will be required to serve, hour-after-hour over a stretch of a typical day, exactly 20 landings per hour. Suppose now that, through an extraordinary quirk in airline scheduling, all 20 landings scheduled for each hour always manage to arrive in the vicinity of the final approach gate\* simultaneously, at the beginning of the hour. In this case, the first of the aircraft to land will do so immediately, say, at the zero-th minute of the hour, whereas the last of the 20 airplanes will land at the beginning of the 38th ( $=2 \times 19$ ) minute. Thus, the average delay per aircraft will be 19 minutes and the runway (for the 4 minute average delay threshold) would be said to operate at a rate over its practical hourly capacity, i.e. PHCAP is less than 20 in this case.

By contrast, consider now the (equally extraordinary) case in which aircraft always arrive in the vicinity of the runway spaced exactly 3 minutes apart. Since the minimum required interval between landings is 2 minutes, all aircraft would land with no delay whatsoever. PHCAP is higher than 20 now.

In the above example, the hourly capacity of the runway, according to the AIL Handbook definition, would obviously be different in the two cases despite the fact that the runway and the associated separation rules are identical in the two cases. Obviously, this is a highly undesirable feature. Yet, there is one capacity-related fact in our example that is independent of the characteristics of the demand for access to the runway, viz. the runway can serve aircraft at the rate of 30 per hour. The definition of hourly capacity which is becoming increasingly accepted in recent years focusses on precisely this quantity, the rate of service per hour.

\*See Glossary in Appendix A.

More precisely, the hourly capacity of a runway -- or a combination of runways -- is now defined as the average number of movements that can be conducted on the runway(s) over an hour under continuous demand conditions and without violating ATC separation standards. Capacity defined in this way is also often referred to (for obvious reasons) as maximum throughput capacity, saturation capacity or maximum service rate. The use of the term "average" number of movements recognizes the fact that intervals between aircraft movements on a runway are not constant quantities but vary according to aircraft type, weather conditions, type of operation (landing or takeoff), pilot and air traffic controller performance, navigation system in use, etc. Thus the actual number of movements per hour, even under continuous demand conditions, can vary appreciably and hourly capacity is defined as the average value of this actual number over a large number of observations.

With respect to the model review conducted here, it can now be noted that all models reviewed in this section estimate capacity according to our second definition, i.e. in the "maximum throughput" sense. The new handbook of Airport Capacity (3) which was published by the FAA in 1976, also adopted this definition of hourly capacity. Consequently, the term "hourly capacity" (or simply, "capacity") of a runway(s) will be used henceforth in this review to imply maximum throughput capacity.

Finally, it should be noted that PHCAP, after all, is a derivative measure of hourly capacity (as we define it here). In other words, given the hourly capacity of a runway (or of a combination of runways) and given a time-pattern of demand for runway use, it is possible (at least theoretically) to estimate -- using a delay-oriented runway model -- the level of movements at which the average delay becomes equal to 4 minutes (or whatever is the desired number).



## 1.2 OVERVIEW OF THE MODELS

The models reviewed in this section can all be viewed as descendants of the original work of Blumstein (4,5) in the sense that they use the same basic logic and approach to compute runway capacity. Blumstein's model was extended and modified in a variety of ways by Harris (6), the National Bureau of Standards (7) and Odoni (8) in three projects conducted independently and simultaneously in 1969. All three documents have been reviewed in the 1971 Survey of ATC Models.

The best features of all the models mentioned so far have been incorporated in the model due to Harris (Model A1.1) which is reviewed in this report. Thus Model A1.1 can be said to supersede all earlier models of its type. It is therefore recommended that the reader who wishes to become familiar with models in this area begin by studying Model A1.1. (It may, however, still be worthwhile to also review Reference (4), since that brief paper presents, with remarkable clarity, all the basic concepts in the body of work related to runway capacity.)

Model A1.1 has recently been extended in several ways by Amodeo, Haines and Sinha (Model A1.2). Model A1.2 explicitly takes into account the increasing presence of wide-bodied jets in airport traffic mixes, and makes some necessary minor modifications to Model A1.1 as a result. In addition, this model incorporates a considerably simplified version of the "separation buffers" of Model A1.1, resulting in simplification of the calculations required to compute runway capacity, without any apparent loss in the accuracy of capacity estimates. Model A1.2 does contain some unnecessarily restrictive assumptions for the case of runways used for both landings and takeoffs. For this latter case, the description of the model in the document reviewed is not clearly presented, and may be confusing to the prospective user. All-in-all, Model A1.2 can be considered the state-of-the-art model in Category A1 and its use is recommended. Table 1-1 summarizes the inputs to the model, and Table 1-2 lists the cases covered by it. The MITRE Corporation (METREK division) has a computerized version of this model.

TABLE 1-1. INPUTS TO MODEL A1.2

Aircraft Type Inputs

- Aircraft Mix (Percentage in Each Category)
- Approach Velocities (Knots)
- Final Velocities (Knots)
- Mean Arrival Runway Occupancy Time (Seconds)
- Departure Time to Clear an Intersection (Seconds)
- Standard Deviation of Arrival Runway Occupancy Time (Seconds)
- Number of Standard Deviations of Runway Occupancy Time to be Protected

Separation Standards

- Between Aircraft Sizes (Heavy/Large/Small)
- By Type of Operation (Arrival/Arrival, Arrival/Departure, Departure/Arrival, Departure/Departure)
- By Type of Weather (IFR, VFR)

Miscellaneous Parameters

- Distance to Glide Slope Intercept (N. Miles)
- Length of Common Approach Path (N. Miles)
- Standard Deviation of Metering and Spacing Buffers (Seconds)
- Number of Standard Deviations Protected in Metering and Spacing Buffer

TABLE 1-2. CASES COVERED BY MODEL A1.2

By Weather

- IFR
- VFR

By Type of Operations

- Arrivals Only
- Departures Only
- Mixed (Alternating Landings and Takeoffs Only)

By Runway Configuration

- Single Runway
- Dual Lane Runways
- Intersecting Runways



For the case of a runway which is used for both landings and takeoffs between successive landings, Model A1.2 assumes that exactly one takeoff is always inserted between two successive landings. The main contribution of Model A1.3 is to allow for the possibility that more than one takeoff will be inserted between the successive landings, provided that the time interval between the landings is sufficiently long. Thus Model A1.3 represents a further improvement (in terms of degree of realism) over Model A1.2. However, there are several gaps, confusing points, and errors in the reports that describe Model A1.3 and document the computer version of the model. This leads us to be somewhat hesitant about recommending, at this time, use of the "canned" computer version of this capacity model. This computer program is resident at the computer facility of the FAA at NAFEC in Atlantic City, NJ.

Model A1.4 is typical of (and probably the best among) a number of models which are concerned with runway capacity estimation in the presence of the Microwave Landing System (MLS). The MLS will permit multiple approach paths to a runway (up to a certain distance from the runway threshold) and, therefore, calls for a number of modifications of the Blumstein-Harris genre of models which assume conventional ILS approaches. Model A1.4, due to Tasic and Horonjeff, is well-presented and documented but may require further modifications when the procedures for terminal area operations under the MLS system are further specified in the future.

Model A1.5 is another example of this type of work (multiple approach paths and several types of aircraft). It complements model A1.4 in that it considers more explicitly and in greater detail the effects of accuracy in spacing among aircraft. However, from the practical point of view, the results obtained from the two models should be almost identical, so that little would be gained in going through the more sophisticated analysis in A1.5.

Two other models reviewed here are of rather academic interest because their practical applicability appears questionable.

Horn (Model A1.7) presents a runway capacity model which is primarily concerned with capacity optimization through sequencing by aircraft type and through allocation of different aircraft types to different runways. Unfortunately both of these approaches seem to lie far in the future -- as far as implementation in the ATC environment is concerned. Daellenbach (Model A1.6) is concerned with a runway occupancy time model designed to maximize capacity through optimal placement of high-speed runway exits. Although the mathematics of the optimization technique is interesting, the practical significance of the approach is probably minimal.

Another way to estimate the hourly capacity of a runway (or runways) is to simulate operations on the runway(s) under continuous demand conditions for many hours and observe the average number of operations conducted per hour. That number is, of course, the runway capacity. Since the "physics" of the runway usage process are well understood (in cases of ever-present demand) it is a relatively simple task to simulate this process. This is done, for example, in the model described in reports by Ball and Dolat (refer to Section 1.8). The disadvantages of this approach are its cost, and the usual problems of statistical credibility (how many hours should be simulated? What is the statistical confidence in the results?) associated with simulations. Thus, if the objective is only to estimate runway capacity, we believe that simulation is not competitive with the analytical models (e.g. models A1.1 through A1.3) discussed above.

This does not mean that simulation of operations on runways may not be justified if the objective is to observe the problems encountered by individual aircraft when they operate at an airport, or to estimate delays associated with specific levels of demand and modes of operation. Indeed, as will be seen in Sections 2 and 3, many delay-oriented runway models and complete airport models do indeed use aircraft-by-aircraft simulation of runway operations.

### 1.3 GENERAL OBSERVATIONS ON RUNWAY CAPACITY MODELS

The following remarks apply primarily to Models A1.1 through A1.4 and to related models (References 4 through 8 of Section 1.5, and the reports listed in Section 1.8).

The problem of estimating runway hourly capacity is probably the best understood among the important problems related to the National Airspace System. The problem can be considered to be essentially "solved". This should be taken to mean that: (i) the available models are quite realistic in their representation of the actual situation at airports; and (ii) the capacity estimates obtained from the models appear to be quite accurate and typical of the numbers that can be observed in practice. Thus, the state of the art can be pronounced satisfactory at this point, although some further work will undoubtedly be necessary in connection with the proposed adoption of MLS-related procedures in the terminal area.

A second observation is that the "physics" of the capacity models are so simple that they can be represented by a few basic mathematical relationships which, in turn, provide the required estimates of capacity. For this reason, none of the models reviewed here require a computer simulation of runway operations. Instead, the estimates of capacity are obtained by exploring the basic analytical relationships over the whole range of variable values and aircraft mix combinations. Appropriate probability distributions are used to represent these ranges of values and the corresponding probabilities. Thus, these models are analytical and probabilistic.

For the same reason, computer implementation of capacity models is a straightforward matter. For instance, it is a relatively simple task to prepare a computer program to implement Model A1.2. Computer-related costs (i.e., running time, preparation of inputs, etc.) should also be minimal.

On the other hand, it should be emphasized that the accuracy of the numerical estimates of capacity depends critically on the accuracy of certain of the model inputs. Especially important are the values used for the separation standards, and the air traffic



controllers' operating strategies (with regard to the mixing and sequencing of landings and takeoffs). Some good typical input values are provided in the report by Amodeo et al. which documents Model A1.2.

Finally it should be noted that when the number of distinct (from the model's point of view) aircraft categories using the runways is relatively small (say 3 or 4 categories such as "wide-body jets," "4-engine conventional jets," "3- and 2-engine conventional jets," etc.) it is not even necessary to use a computer. The calculations required by the recommended Model A1.2 can be easily performed with any pocket-size electronic calculator. (Approximate estimates of runway capacities for a large number of conceivable input and runway combinations can also be found in the recent handbook Techniques for Determining Airport Airside Capacity and Delay prepared by the Douglas Aircraft Company-reference 3, section 1.5).

#### 1.4 CONCLUSIONS AND RECOMMENDATIONS

1. Hourly capacity of runways is now generally defined in terms of the maximum throughput rate (or saturation capacity, or maximum service rate) concept.
2. The state of the art in the area of capacity-oriented runway models is satisfactory. The better models are quite realistic and produce good estimates of runway capacity.
3. Model A1.2 is recommended as the prototype model to use for capacity calculations. The model is simple, it can be easily implemented in a computer, and, in many cases, can also be used with only a pocket electronic calculator. The description of the model in the principal available document is not clearly presented in some areas, and requires careful interpretation by the reader.
4. Users of capacity-oriented models should be aware of the high sensitivity of the numerical estimates of capacity to the values used for some of the inputs, especially separation standards.

### 1.5 BACKGROUND REFERENCES

1. Airborne Instruments Laboratory, Airport Capacity, Deer Park, New York, June 1963. Prepared for Federal Aviation Agency (PB 181553).
2. Airborne Instruments Laboratory, Airport Capacity Handbook, 2nd Edition, FAA Report No. SRDS-68-14 (AD 690-470), June 1969.
3. Douglas Aircraft Company, Techniques for Determining Airport Airside Capacity and Delay, FAA Report No. FAA-RD-74-124, June 1976.
4. Blumstein, A., "The Landing Capacity of a Runway," Operations Research, Vol. 7 (1959), pp. 752-763.
5. Blumstein, A., An Analytical Investigation of Airport Capacity, Cornell Aeronautical Laboratory, Report No. TA-1358-8-1, June 1960.
6. Harris, R.M., Models for Runway Capacity Analysis, The MITRE Corporation, Washington, D.C., Technical Report MTR-4102, 1969.
7. National Bureau of Standards, Analysis of a Capacity Concept for Runway and Final Approach Airspace, Report 10111, 1969.
8. Odoni, A.R., An Analytic Investigation of Air Traffic in the Vicinity of Terminal Areas, M.I.T. Operations Research Center, Technical Report No. 46, December 1969.



## 1.6 MODELS REVIEWED AND SUPPORTING DOCUMENTS

### Model A1.1

Harris, R.M., Models for Runway Capacity Analysis, Rev. 2, Report MTR-4102, Rev. 2, The MITRE Corporation, McLean, VA., December 1972. [A1; A2]\*

### Model A1.2

Amodeo, F.A., A.L. Haines and A.N. Sinha, Concepts for Estimating Capacity of Basic Runway Configurations, Report MTR-7115, The MITRE Corporation, McLean, VA, March 1977. [A1]

### Model A1.3

Hockaday, S.L.M. and A.K. Kanafani, "Developments in Airport Capacity Analysis," Transportation Research, 8, No. 3, pp. 171-180 (August 1974). [A1]

Douglas Aircraft Company, Procedures for Determination of Airport Capacity, Volumes I and II, Report FAA-RD-73-11, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, April 1973. [A3; A1]

Ball, C.T., Model User's Manual for Airfield Capacity and Delay Models, Books 1 and 2, Report FAA-RD-76-128, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, November 1976. [A3; A1]

### Model A1.4

Tosic, V. and R. Horonjeff, "Effect of Multiple Path Approach Procedures on Runway Landing Capacity," Transportation Research, 10, No. 5, pp. 319-329 (October 1976). [A1]

Tosic, V. and R. Horonjeff, Models for Estimating Landing Capacity with Microwave Landing Systems (MLS), Special Report No. 123, University of California at Berkeley, Institute of Transportation Studies, Berkeley, CA, 1975. [A1]

\*[Primary category; secondary category]

Model A1.5

Smith, A.P., An Extension of the Throughput Runway Capacity Methodology to Include Multiple Glide Path Lengths and Angles, Report MTR-6338, The MITRE Corporation, McLean, VA, May 1973. [A1]

Model A1.6

Daellenbach, H.G., "A Dynamic Programming Model for Optimal Location of Runway Exits," Transportation Research, 8, No. 3, pp. 225-232 (August 1974). [A1]

Model A1.7

Horn, W.A., Extension of a Capacity Concept to Dual-Use Runways and Multi-Runway Configurations, Report FAA-RD-71-19, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, December 1971. [A1]

# 1.7 ATTAINABILITY OF COMPUTER PROGRAMS

Model	Is Computer Program Required?	Program Listing Included In Reviewed Documents?	Program User's Guide Publicly Available?	Can Computer Program be Readily Written?	Individuals (if known) and Organization to Contact for More Information on the Model
AI.1	Yes	No	No	Yes	R.M. Harris The MITRE Corporation 1820 Dolley Madison Blvd. McLean, VA 22102
AI.2	Yes	No	No	Yes	A.N. Sinha The MITRE Corporation 1820 Dolley Madison Blvd. McLean, VA 22102
AI.3	Yes	No	Yes	No	John VanderVeer Federal Aviation Administra- tion NAFEC Atlantic City, NJ 08405
AI.4	Yes	Yes	Yes	Yes	None Currently
AI.5	Yes	No	No	Yes	R.M. Harris The Mitre Corporation 1820 Dolley Madison Blvd. McLean, VA 22102
AI.6	Yes	No	No	No	Refer to detailed model review
AI.7	Yes	No	No	No	W.A. Horn National Bureau of Standards U.S. Dept. of Commerce Washington, DC 20234



## 1.8 OTHER RELATED REPORTS

Ball, C.T., Analysis of Dual Lane Runways, Report FAA-RD-73-97, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC., March 1974. [A1]

Dolat, V.S. and J.C. Koegler, Dual Lane Runway Study, Report FAA-RD-73-60, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, May 1973. [A1]

Douglas Aircraft Company, Technical Report on Airport Capacity and Delay Studies, Report FAA-RD-76-153, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, June 1976. [A3; A1]

Douglas Aircraft Company, Techniques for Determining Airport Airside Capacity and Delay, Report FAA-RD-74-124, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, June 1976. [A3; A1]

Douglas Aircraft Company, Supporting Documentation for Technical Report on Airport Capacity and Delay Studies, Report FAA-RD-76-162, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, November 1976. [A3; A1]

Haines, A.L., Concepts for Determination of Longitudinal Separation Standards on Final Approach, Report MTR-7047, The MITRE Corporation, McLean, VA, October 1975, [B1; A1]

Ito, M., "Air Traffic Simulation," in (Japanese) Electronics and Communications, 57, pp. 58-66 (November 1974). [A1]

Judem, R.J., A Computer Model for Determining Runway Capacity, S.B. Thesis (unpublished), MIT Electrical Engineering Department, Cambridge, MA, June 1973. [A1]

Sinha, A.N. and A.L. Haines, Longitudinal Separation Standards on Final Approach for Future ATC Environments, Report MTR-6979, The MITRE Corporation, McLean, VA, October 1975. [B1; A1]

#### 1.9 REPORTS NOT REVIEWED

Hooton, E.N., P.H. Stafford, M.A. Warskow and W.A.T. Bonda, Analyses of the Capacity of Dulles International Airport, The Brandt Drift-Off Runway and the Monroe Triple Flow Airport Configuration, Report 7601-2, Airborne Instruments Laboratory, Deer Park, NY, undated. [A1]

Hughes, N.H., K. Watling and R.A. Harlow, Some Preliminary Studies of Factors Influencing Airport Capacity Including Curved Final Approach Paths, March 1971. [A1] (AD-734276)

Iyer, R.R. and D. Goldman, An Advanced Air Traffic Management Concept Based on Extensions of the Upgraded Third Generation ATC System: System B; Airport Capacity Analysis, Report MTR-6419-Ser. 6, The MITRE Corporation, McLean, VA, 1973. [A1]

## 2. DELAY-ORIENTED RUNWAY MODELS (CATEGORY A2)

Models in this category are primarily oriented toward providing estimates of delays that are due to runway congestion. The interested reader should also refer to Section 3 (Complete Airport Models) which reviews several additional models that estimate runway delays in the course of studying airside operations throughout the airfield (and not solely on the runways).

A listing of Category A2 models reviewed and supporting documents is contained in Section 2.7. Attainability of computer programs for the models in this category is indicated in Section 2.8.

### 2.1 BACKGROUND INFORMATION

A considerable number of models have been developed in this area over the last several years. They can be divided into analytical models (which attempt to estimate delays through the formulation and manipulation of mathematical expressions) and simulation models (which generate -- through a computer program -- aircraft, move them through the runway system, and collect statistics on the delays experienced by each aircraft).

In both categories the quality of the available models has improved dramatically in comparison to those reviewed in the 1971 survey of ATC models. The improvement in simulation models has been evolutionary, characterized by increased sophistication in the models' logic. With regard to analytical models, on the other hand, there has been a "breakthrough" in the available methodology as will be explained below. This has rendered these analytical models fully competitive -- at least for certain types of questions -- with the simulations with respect to accuracy and realism.

In the following sections the two types of delay-oriented models are reviewed separately and the advantages and disadvantages



of each type (analytical/simulation models) as a whole are discussed.

## 2.2 ANALYTICAL MODELS

Analytical delay-oriented runway models are based on queueing theory, a major branch of operations research which has attracted a lot of attention in the years since World War II. Until recently, the major deficiency of these delay-oriented runway modes was that, as in most of classical queueing theory, these models were developed for "steady-state" conditions. In other words, it was assumed that the average rate of demand (i.e. the number of aircraft requesting to land at or to takeoff from the airport in question) and the average service rate (i.e. the capacity of the airport -- see Section 1) remain constant over time, so that a long-term equilibrium condition can be reached. For typical examples of these older analytical models the reader is referred to Blumstein (1), Harris (4), and Odoni (5) (see Section 2.6).

Obviously, the assumption of a constant rate of demand and a constant rate of service at an airport is an unrealistic one. Demand changes -- often drastically -- from hour to hour in the course of a typical day at most airports. The service rate (capacity) may also change as a result of changes in weather, aircraft mix, runway configurations, etc. The reason for the steady-state assumption was the virtual lack of any truly usable, closed-form results from queueing theory applicable to congested systems with time-varying demand or service rates.

Two early attempts to confront the problems caused by time-varying demand and service rates are noteworthy. One is the study of delays at New York's airports performed by Carlin and Park in 1969. In connection with this work, a cumbersome but ingenious model was developed (2) for predicting delays for any given time-dependent demand profile. The second early model of interest, due to Galliher and Wheeler (3), is in many ways a precursor to the more recent models reviewed below, containing all of the latter models' main ideas. Although both of the aforementioned

models have by now been surpassed, future researchers in this area might be well-advised to study the related reports (both well-written).

The major "breakthrough" in analytical models is marked by the work of Koopman (see Section 2.7, Model A2.1). Koopman made the following two key observations:

a) It may be impossible to obtain usable, closed-form expressions for delay statistics associated with queueing systems with time-varying demand and service rates; it is, however, quite simple to write sets of differential equations that describe the behavior over time of some of these time-dependent queueing systems, and then to solve these equations numerically with the help of the computer -- for any given set of input values.

b) Among the queueing systems that can be described and analyzed in this way are two systems that provide an upper limit and a lower limit for the delays experienced by aircraft using an airport (these are queueing systems with negative exponential and with constant service times, respectively); moreover, in many airport situations these upper and lower limits are not significantly different, thereby limiting the actual delay statistics to a narrow range of values.

From the practical point of view, Model A2.1 has been surpassed by Model A2.2 which covers a wider set of cases and is very efficient (computationally). However, it is strongly recommended that the potential user of Model A2.2 become familiar with the report accompanying Model A2.1 (Section 2.7), which contains the theoretical foundation for Models A2.1, A2.2 and A2.3.

Model A2.2 is the state-of-the-art analytical, delay-oriented runway model. It extends Model A2.1 to the case of multiple runways and it is coded in a sophisticated way that offers high numerical accuracy and computational efficiency. The preparation of inputs for Model A2.2 is also very simple and can be accomplished in a minimum amount of time. Model A2.2, however, suffers from two important disadvantages (which are also shared by Models A2.1 and A2.3):

- i) The model does not compute the capacity of the runway system in use but requires that capacity as an input.
- ii) The model does not make a distinction between landings and takeoffs; thus for the cases when a runway is used for mixed operations (landings and takeoffs), the model cannot provide separate statistics for each type of operation but only average figures per "movement" (irrespective of type).

The first disadvantage can be easily overcome by using a capacity-oriented runway model (such as Model A1.2 reviewed in the previous section) to compute the required capacity input to Model A2.2. The second problem, however, is more fundamental and cannot be avoided with the existing model.

Despite this problem, use of Model A2.2 is recommended, especially where quick, approximate estimates of delay are required and available resources are limited. These circumstances may exist when performing cost-benefit analyses, or a study aimed at determining the level of airport demand at which delays may approach unacceptably high values.

Model A2.3 uses the same general methodology as Model A2.2 but is surpassed by the latter. That is, Model A2.2 contains more features and seems more carefully programmed for efficient computation than A2.3. Model A2.3 contains the equations for only the "upper limit" queueing system of Model A2.2 (and omits those for the lower limit system).

### 2.3 SIMULATION MODELS

Three simulation models reviewed in this section seem to offer satisfactory tools for obtaining delay estimates on runway systems. The best documented among these and, therefore, the one whose use we can recommend most confidently, is Model A2.4 developed at the National Bureau of Standards. This model appears to be efficient and easy-to-use (particularly for airport capacity calculations) with several convenient features.



It is less clear, however, that complex runway configurations or controller operating strategies can be simulated by this model.

The AIRSIM model of the Boeing Company (Model A2.5) is characterized by a level of detail (especially with respect to simulating aircraft performance characteristics) which seems unequalled by any other model reviewed here (including those in Section 3). This statement, however, is a tentative one due to the sketchiness of the model documentation material available to the reviewers with regard to AIRSIM and the lack of information on the extent to which AIRSIM has been exercised to date.

Model A2.6 is an impressive and clearly described effort from the RTM Planning Partnership of Australia. This simulation model emphasizes estimation of annual delay statistics and some of its features are geared in this direction. Particularly useful are the various options that this model provides for simulating the time of arrival of aircraft in the vicinity of the airport.

In concluding this discussion, it is perhaps worth pointing out that simulation models, by virtue of the way in which they operate, can also be used to determine the capacity of a runway (or combination of runways) where capacity is defined, as in Section 1 as the maximum service rate. To do this, all that is needed is to "saturate" the runway system with the appropriate mix of aircraft and operations and then to count the average number of aircraft that are served (according to the operational rules in force) per hour. It is our recommendation, however, that one of the models reviewed in Section 1 be used if the analyst is solely interested in capacity estimates (and not in associated delay figures).

## 2.4 GENERAL OBSERVATIONS

The main remaining question to be addressed concerns the choice between analytical and simulation models for estimating delay. As is almost always the case whenever this question arises, here too there is no clear-cut answer. In general, the proper choice depends on the use to which the delay estimates will be put. Analytical models (such as A2.2) would appear to be preferable when good general estimates of delay (such as average number of queued aircraft, average waiting time, probability of having to wait more than X minutes, etc.) are desired. On the other hand, if detailed estimation of delays suffered by specific types of aircraft or specific types of operations is necessary (or if it is desirable to observe the level of congestion at specific points on the airfield), then a simulation is called for. In addition, the simulation models reviewed can accommodate a much higher level of detail regarding runway configurations, exit placements, etc. than is possible with analytical models.

The prospective model user should be aware of the limitations of the models in both categories, especially of the need for careful statistical analysis of results obtained from simulation models in order to establish the level of statistical confidence.

As a final comment, we note that, despite claims to the contrary, none of the delay-oriented runway models reviewed here has been truly validated (i.e. by ascertaining that model outputs agree with real-world delay data). The reason for this peculiar (and unfortunate) circumstance is due primarily to the great difficulty of collecting reliable delay data at airports, and identifying the component of delay due to runway congestion (as opposed to mechanical causes, delays occurring upstream in the ATC system, delays due to pilot preferences or controller strategies, etc.).

## 2.5 CONCLUSIONS AND RECOMMENDATIONS

1. The state of the art in the area of delay-oriented runway models has advanced considerably over the last few years. The better models are quite satisfactory although several deficiencies still exist.
2. An important decision that the analyst must make before undertaking a runway delay study is whether to use an analytical or a simulation model. The proper choice is determined largely by the level of detail desired and the available resources for the study.
3. Model A2.2 is recommended as an analytical model for quite accurate, and computationally inexpensive, estimates of delay. The model requires runway capacity to be provided as an input and does not provide separate delay statistics for landings and for takeoffs.
4. Simulation Models A2.4, A2.5 and A2.6 all seem acceptable and are recommended for use when more detailed analysis than is possible through analytical models is desired. The conclusion regarding Model A2.5 is tentative due to the abbreviated nature of the model documentation available to the reviewers.
5. None of the delay-oriented runway models has been truly validated.



## 2.6 BACKGROUND REFERENCES

1. Blumstein, A., An Analytical Investigation of Airport Capacity, Cornell Aeronautical Laboratory, Report No. TA-1358-8-1, June 1960.
2. Carlin, A. and R.E. Park, "A Model of Long Delays at Busy Airports", in Journal of Transport Economics and Policy, Vol. 4, No. 1, January 1970, pp. 37-52.
3. Galliher, H.P. and R.C. Wheeler, "Nonstationary Queueing Probabilities for Landing Congestion of Aircraft," in Operations Research, Vol. 6 (1958), pp. 264-275.
4. Harris, R.M., Models for Runway Capacity Analysis, The MITRE Corporation, Washington, D.C., Technical Report MTR-4102, Rev. 2, December 1972.
5. Odoni, A.R., An Analytic Investigation of Air Traffic in the Vicinity of Terminal Areas, M.I.T. Operations Research Center, Technical Report No. 46, December 1969.

## 2.7 MODELS REVIEWED AND SUPPORTING DOCUMENTS

### Model A2.1

Koopman, B.O., Analytical Tools for the Study of Airport Congestion, Arthur D. Little, Inc., Cambridge, MA, 1971. [A2]

Koopman, B.O., "Air Terminal Queues Under Time-Dependent Conditions," Operations Research, 20, No. 6, pp. 1089-1114 (November-December 1972). [A2]

### Model A2.2

Hengsbach, G. and A.R. Odoni, Time-Dependent Estimates of Delays and Delay Costs at Major Airports, Report R75-4, MIT Flight Transportation Laboratory, Cambridge, MA., January 1975. [A2]

### Model A2.3

Battelle Columbus Laboratories, Airport Demand/Capacity Analysis Methods, Preliminary Report, Columbus, OH, September 1974. [A2]

Chadwick, J.W., V.J. Drago and D.G. Ullman, Study for the Conversion of Short-Haul Airports: Interim Technical Report, Report on file at U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, March 1974. [A2]

Battelle Columbus Laboratories, Prototype Cost/Benefit Results and Methodology for UG3RD System Capacity and Safety, Columbus, OH, June 1975. [A2; B1, A7]

### Model A2.4

Gilsinn, J.F., A Simulation Model for Estimating Airport Terminal Area Throughput and Delays, Report FAA-RD-71-9, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, May 1971. [A2; A1]

Gilsinn, J.F., Validation of Maximum Airport Throughput Levels Estimated by the DELCAP Simulation Model, Report FAA-RD-75-66, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, January 1975. [A2; A1]

Gilsinn, J.F., Validation of the DELCAP Airport Simulation Model, Report FAA-RD-75-154, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, July 1975. [A2; A1]

Gilsinn, J.F., Validation of an Airport Simulation Model, Report NBS-10592, U.S. Dept. of Commerce, National Bureau of Standards, Washington, DC, 1976. [A2; A1]

Model A2.5

The Boeing Company, Descriptions of the AIRSIM, CAPACITY and GOSIM Computer Programs, unpublished document-private communication, Seattle, WA, undated. [A3; A1]

Model A2.6

Atack, M.J., "A Simulation Model for Calculating Annual Congestion Delay Arising from Airport Runway Operations," Journal of Operational Research Society, 29, No. 4, pp. 329-339 (1978). [A2]



## 2.8 ATTAINABILITY OF COMPUTER PROGRAMS

Model	Is Computer Program Required?	Program Listing Included In Reviewed Documents?	Program User's Guide Publicly Available?	Can Computer Program Be Readily Written?	Individuals (if known) and Organization to Contact for More Information on the Model
A2.1	Yes	No	No	No	Bernard O. Koopman A.D. Little, Inc. Acorn Park Cambridge, MA. 02140
A2.2	Yes	No	No	No	Amedeo R. Odoni Room 33-404, M.I.T. Cambridge, MA. 02139
A2.3	Yes	No	Yes	No	Robert Rogers Battelle-Columbus Laboratories 505 King Avenue Columbus, OH 43201
A2.4	Yes	Yes	Yes	No	Judith F. Gilsinn National Bureau of Standards U.S. Department of Commerce Washington, D.C. 20234
A2.5	Yes	No	No	No	R. Erwin Boeing Commercial Airplane Co. P.O. Box 3707 Seattle, WA 98124
A2.6	Yes	No	Unknown	No	M.J. Atack RTM Planning Partnership Sydney, Australia

## 2.9 OTHER RELATED REPORTS

Chesney, E.S., Estimation of UG3RD Delay Reduction, Report FAA-AVP-77-7, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC., January 1977. [A2]

Condell, H.M. and A.S. Kaprelian, Airline Delay Trends 1973-1974: A Study of Block Time Delays, Ground and Airborne, for Scheduled Air Carriers, Report DOT-TSC-FAA-76-24, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA., 1976. [A7; A2]

Harris, R.M., Models for Runway Capacity Analysis, Rev. 2, Report MTR-4102, Rev. 2, The MITRE Corporation, McLean, VA., December 1972. [A1; A2]

Odoni, A.R. and P. Kivestu, A Handbook for the Estimation of Airside Delays at Major Airports (Quick Approximation Method), Report NASA-CR-2644, National Aeronautics and Space Administration, Washington, DC, June 1976.

Scalea, J., A Comparison of Several Methods for the Calculation of Airside Airport Delay, S.M. Thesis (unpublished), MIT Dept. of Aeronautics and Astronautics, Cambridge, MA, June 1976. [A2]

## 2.10 REPORTS NOT REVIEWED

Kiefer, D.W., A Linear Programming Approach to Airport Congestion, S.M. Thesis, Purdue University, West Lafayette, IN, 1970. [A2]

Stamp, R.G., The Magnitude and Causes of Departure Delays at Heathrow, Summer and Spring 1975, Civil Aviation Authority, United Kingdom, 1976. [A2]

### 3. COMPLETE AIRPORT MODELS (CATEGORY A3)

Models in this category are concerned with all (or most) aspects of airside operations at an airport\*. Thus, in addition to runway operations, these models cover taxiway, apron, and aircraft gate operations. This is in contrast to the exclusively runway-oriented models reviewed in Sections 1 and 2. Since overall airport capacity and levels of delay are, most often, largely determined by the capacity of the runway system and by delays related to traffic congestion on the runways, those readers who are interested in this category of models would be well-advised to refer also to Sections 1 and 2.

A listing of Category A3 models reviewed and supporting documents is contained in Section 3.3. Attainability of computer programs for the models in this category is indicated in Section 3.4.

#### 3.1 OVERVIEW OF THE MODELS

The six models reviewed in this section cover a wide spectrum of methodologies, ranging from highly detailed and complex simulation models to very simple analytical models. The numbering of the models in this section is intended to reflect this gradation in complexity, with Models A3.1 and A3.2 being the most detailed and computer-oriented and Model A3.6 being the simplest one of those reviewed.

Models A3.1 and A3.2 are large-scale simulations designed to be adaptable to different airport configurations. They are capable of simulating in considerable detail, operations on runways, taxiways, aprons and gates. Each is claimed to have the ability to simulate airports with up to five active runways. This would cover all existing airports in the world, with the possible exception of some Chicago O'Hare configurations (6 active runways).

\*Models of airport landside are not included in this report.



Unfortunately, our review could not be carried out to the same depth for both of these models. Model A3.1, the Delay Simulation Model (DSM), has been developed with extensive funding from the Federal Aviation Administration. Several documents have been published describing the logic, assumptions and limitations of DSM. By contrast, Model A3.2, the Ground Operations Simulation (GOSIM) has apparently been developed with internal funding by the Boeing Company (together with its "sister packages" AIRSIM and CAPACITY - see Section 2), with minimal documentation available to the reviewers. In addition, whereas at least one version of DSM is generally accessible to interested users through the FAA, it is our understanding that GOSIM is a proprietary model of the Boeing Company. Therefore, few meaningful comparisons could be made between the two models.

While DSM provides a tool for airport simulations at a high level of detail (up to 5 active runways and 200 active aircraft), the prospective user should be aware of the large amount of input data required, high learning and computing costs, and several limitations, which are discussed in the detailed review of the model (see Part III). DSM also places great emphasis on the simulation of airport taxiways and aprons as opposed to runways. However, it is the runways which are usually more important from the point of view of both capacity and delays.

The GOSIM model seems to be capable of simulating a level of detail and airport complexity similar to that of DSM. It contains some logical features which are superior to corresponding features in DSM and there are indications that it may possess greater flexibility. On the other hand, the extent to which this model has been exercised is unclear and it has certainly not been subjected to the kind of review given to DSM in recent years.

Due to lack of detailed information on the GOSIM model, the comparisons between it and DSM must necessarily end here. At a more general level, however, it is our assessment that any decision to use simulation models of the scale of Models A3.1 and A3.2 should be made carefully, with full consideration of both the

costs and the benefits associated with such use. While it is true that such models can provide more detailed information on many aspects of airport operations than any well-chosen set of analytical models, unless the user is truly interested in exactly this type of specialized information (e.g., to what extent is a specific taxiway segment utilized?), the use of state-of-the-art detailed simulation models is probably not cost-beneficial.

As an example, suppose that the main concern (as is very often the case) in an airport analysis is the amount of delay associated with a given level of demand and a given demand profile. The analyst might then be well advised to concentrate on the runway system (using one of the analytical or simulation models reviewed in Section 2, e.g. Models A2.2, A2.4, A2.5 or A2.6) and to ascertain, virtually by inspection, that the taxiway system does not impose any major additional delays on airport traffic (which is the case most of the time). If any additional "trouble spots" exist on the taxiway network, they could then be analyzed separately. In this way the analyst will avoid the task of obtaining and computer coding the large amount of input data (often requiring data that are difficult to obtain) and high learning and computer costs that are likely to be associated with use of large scale simulations such as Models A3.1 and A3.2.

Having offered this assessment, it should be added that it is the opinion of the reviewers that models such as A3.1 and A3.2, while cumbersome in their present form, represent the "wave of the future." The next generation of models of this type will probably offer much simpler means of describing airport geometry to the computer (for an indication of the level of effort now required, see the evaluation of Model A3.1 in Part III), and will likely rely far less on the user for specification of detailed controller logic, aircraft separation rules, and demand profiles.

Model A3.3 can be said to be an antecedent of Models A3.1 and A3.2. It is a location-specific simulation model (Dallas-Ft. Worth) apparently limited in its flexibility and level of detail, and contains few probabilistic features. It has been superseded by GOSIM and DSM.

Model A3.4, the Airport Performance Model (APM) which was developed at the Transportation Systems Center/DOT, is a simulation model that is not oriented toward a detailed simulation of operations, but instead is aimed at deriving delay estimates which are sufficiently accurate to be useful in airport investment analyses and in calculations of energy consumption and polluting emissions at each airport of interest. The model uses a very simple scheme to simulate arrivals and departures. It represents each airport as a single runway with an acceptance rate equal to the capacity of the actual runway configuration in use. A fixed OAG-type schedule of arrivals and departures is then processed through the runway and (deterministic) estimates of delay for each time period simulated are obtained. APM can be considered a simulation model with uses comparable to those of some of the analytical, delay-oriented runway models which are reviewed in Section 2. We have reservations about the accuracy of the delay estimates produced by APM due to the deterministic nature of its analysis, especially at low runway utilization rates when probabilistic phenomena are the main causes of delay. However, the model can be useful in a preliminary airport investment analysis. That usefulness is enhanced by the extensive data base that has been provided for APM. The data base currently includes 31 of the busiest airports in the United States, and includes data on energy consumption, pollution emission characteristics, and direct operating costs for a large number of aircraft types.

APM also includes a section that computes aircraft delays due to gate congestion at airport terminals. We do not recommend use of that part of the model due to the fact that the analysis is based on what we believe to be unrealistic assumptions (see detailed model review in part III).

Model A3.5 represents a family of simple analytical taxiway and gate capacity models, rather than a single one. These models were developed as part of the project that eventually led to the publication of the most recent FAA Handbook on airport capacity and delay, FAA-RD-74-124 (see Section 3.3, Model A3.5). Thus they are products of the same effort that led to development of Model



A1.3, reviewed with the capacity-oriented runway models of Section 1. Indeed the analytical approach and the expressions derived are very similar to those used for runway capacity calculations. The mathematical expressions in Model A3.5 are very adequate for estimating taxiway and gate capacity. (In fact, the analysis can be criticized for using an "overkill" of mathematical symbolism in order to "solve" what are rather simple problems.) Model A3.5 can be combined with one of the better runway capacity models of Section 1 to provide capacity estimates for all components of airport airside. (As discussed previously, it is highly unlikely that the taxiway network will actually impose any significant capacity constraints beyond those imposed by the runways and, occasionally, by the gate complex.)

In connection with Model A3.5, it should be added that the above referenced FAA Handbook of airport capacities and delays also provides delay nomographs from which estimates of taxiway and gate delays can be read. The capacity estimates obtained from Model A3.5 are among the "givens" that the Handbook user needs in order to read these delays from the nomographs. We note here that the set of "delay curves" in the nomographs violates basic principles of queueing theory and therefore is probably incorrect. Consequently this nomograph procedure should not be used for estimating taxiway and gate delays.

The last model reviewed in this Section was used in connection with an assessment of the need for additional Airport Surface Detection Equipment (ASDE) at major airports. Model A3.6 represents the extreme opposite of Models A3.1 and A3.2 due to the degree of simplification that characterizes it. It represents each airport as a single "black box" server with a constant acceptance rate over each hour and computes delays through a simple deterministic analysis by distributing demand, rather arbitrarily, within hours and among hours. This model would, for instance, estimate zero delay at an airport where total demand at the "peak 20 minutes" of the peak hour is as high as 99 percent of the acceptance rate during that hour, a patently false result (see model review in Part III). This oversimplified approach should

be used only in cases where a very approximate, preliminary level of analysis is appropriate.

### 3.2 GENERAL OBSERVATIONS

From discussion of the models reviewed in this Section and taking into consideration the models reviewed in Sections 1 and 2, the following general observations can be made:

1) An adequate "technology" is available at this time for modeling almost all aspects of airport airside operations to any desired degree of detail. The state of the art in this respect has made important strides during the 1970's.

2) The most important decision that an airport analyst (and potential model user) must reach with regard to selecting a model concerns the level of detail required to examine each problem at hand. A wrong decision in this respect can be costly. "Overkill" can be very expensive in terms of time, manpower resources, and money. On the other hand, using a model with an inadequate level of detail will result in either insufficient accuracy or insufficient information, or both.

3) While it is reasonably certain that the airport capacity estimates provided by the better models in this Section and in Section 1 are quite accurate, the same cannot be said of the delay estimates produced by the models in this Section and in Section 2. None of the available models has been truly validated to date with respect to delay estimates (despite occasional claims to the contrary). The main reasons for this are the following: first, it is very difficult to obtain a sufficient amount of accurate and reliable data on airport delays in any selected airport due to observation problems, the propagation of delays "upstream" in the ATC system, and the multiplicity of potential sources of delay; second, the statistical analysis needed before a delay model can be pronounced "validated" is highly complex and extensive.

### 3.3 MODELS REVIEWED AND SUPPORTING DOCUMENTS

#### Model A3.1

Ball, C.T., Model User's Manual for Airfield Capacity and Delay Models, Books 1 and 2, Report FAA-RD-76-128, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, November 1976. [A3; A1]

Peat, Marwick, Mitchell and Co., User's Manual, Airfield Simulation Model, unpublished, San Mateo, CA, April 1977. [A3; A1]

Douglas Aircraft Company, Technical Report on Airport Capacity and Delay Studies, Report FAA-RD-76-153, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, June 1976. [A3; A1]

#### Model A3.2

The Boeing Company, Descriptions of the AIRSIM, CAPACITY and GOSIM Computer Programs, unpublished document-private communication, Seattle, WA, undated. [A3; A1]

#### Model A3.3

Brant, A.E., Jr., and P.J. McAward, Jr., "Evaluation of Airfield Performance by Simulation," Journal of Transportation Engineering (ASCE), 100, No. 2, pp. 505-522 (May 1974). [A3]

#### Model A3.4

Bellantoni, J.F., H.M. Condell, I. Englander, L.A. Fuertes, and J.C. Schwenk, The Airport Performance Model, Volumes I and II, Report FAA-ASP-78-10, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, October 1978. [A3]

Hiatt, D., S. Gordon and J. Oiesen, The Airport Performance Model, Report FAA-ASP-75-5, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, April 1976. [A3]

#### Model A3.5

Ball, C.T., Model User's Manual for Airfield Capacity and Delay Models, Books 1 and 2, Report FAA-RD-76-128, U.S. Dept. of



Transportation, Federal Aviation Administration, Washington, DC, November 1976. [A3; A1]

Douglas Aircraft Company, Procedures for Determination of Airport Capacity, Volumes I and II, Report FAA-RD-73-11, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, April 1973. [A3; A1]

Douglas Aircraft Company, Techniques for Determining Airport Airside Capacity and Delay, Report FAA-RD-74-124, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, June 1976. [A3; A1]

#### Model A3.6

Baran, G. and R.A. Bales, A Preliminary Requirements Analysis for Airport Surface Traffic Control Systems, Report FAA-RD-73-6, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, January 1973. [A3]

Baran, G. and R.A. Bales, Airport Surface Traffic Control Systems Deployment Analysis, Report FAA-RD-74-6, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, January 1974. [A3]

Bales, R.A., Airport Surface Traffic Control Systems Deployment Analysis - Expanded, Report FAA-RD-75-51, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, March 1975. [A3]

### 3.4. ATTAINABILITY OF COMPUTER PROGRAMS

Model	Is Computer Program Required?	Program Listing Included In Reviewed Documents?	Program User's Guide Publicly Available?	Can Computer Program Be Readily Written?	Individuals (if known) and Organization to Contact for More Information on the Model
A3.1	Yes	No	Yes	No	John VanderVeer Federal Aviation Administration, NAFEC Atlantic City, NJ 08405
A3.2	Yes	No	No	No	R. Erwin Boeing Commercial Airplane Co. P.O. Box 3707 Seattle, WA 98124
A3.3	Yes	No	No	No	A.E. Brant, Jr. Tippetts-Abbott-McCarthy-Stratton, Inc. 345 Park Ave. New York, NY 10022
A3.4	Yes	Yes	Yes	No	John Bellantoni U.S. Dept. of Transportation/TSC 55 Broadway Cambridge, MA 02142
A3.5	Yes	No	Yes	Yes	John VanderVeer Federal Aviation Administration, NAFEC Atlantic City, NJ 08405
A3.6	Yes	No	Yes	Yes	Robert A. Bales The MITRE Corporation 1820 Dolley Madison Blvd. McLean, VA 22102

### 3.5 OTHER RELATED REPORTS

Chambers, E.V., T.D. Chmores, W.J. Dunlay, N.D.F. Gualda, F.F. McCollough, C.H. Par and J. Zaniewski, Analysis Procedure for Estimating the Capacity of an Airport: System Definition, Capacity Definition and Review of Available Models, Research Memo No. 27, Dept. of Civil Engineering, University of Texas, Austin, TX, October 1975. [A3]

Douglas Aircraft Company, Supporting Documentation for Technical Report on Airport Capacity and Delay Studies, Report FAA-RD-76-162, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, November 1976. [A3; A1]

Englander, I., An Airport Airside System Model, Report DOT-TSC-OST-71-12, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, June 1971. [A3]

Ferrar, T.A., "The Allocation of Airport Capacity with Emphasis on Environmental Quality," Transportation Research, 8, No. 2, pp. 163-169 (1974). [A3]

Hagerott, R.E., An Overview of Airport Surface Traffic Control - Present and Future, Report FAA-RD-75-144, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, September 1975. [A3]

Hom, R.E. and J.C. Orman, "Airport Airside and Landside Interaction," in Airport Landside Capacity Special Report 159, Transportation Research Board, Washington, DC, pp. 196-208 (1975). [A3]

Horonjeff, R. and D. Maddison, "Computer Analysis of Airfield Operations," Airport Forum, 4, No. 2, p. 41 (June 1974). [A3]

Maddison, D., D.B. Adarkar and R.J. Linn, "New Methods of Determining Airport Capacity and Delay," Paper In Conference on International Air Transportation, Sponsored by the Air Transport Division of the ASCE, San Francisco, CA, March 24-26, 1975. [A3]

Moreland, J.A., "Airport Simulation-A New Approach," Journal of ATC, 14, pp. 21-24 (January 1972). [A3]



Rogers, R.A. and W.C. Bruce, Interactive Computing Techniques in Airport Master Planning, Transportation Research Record No. 588, Transportation Research Board, Washington, DC, 1976. [A3]

U.S. Dept. of Transportation and City of Chicago, O'Hare Delay Task Force Study, Volumes I-III, Report FAA-AGL-76-1, Federal Aviation Administration, Washington, DC, 1976. [A3]

Young, C.S. and J. Nemec, "Systems Analysis in Airport Master Planning," Journal of Transportation Engineering (ASCE), 100, No. TE4, pp. 883-891 (November 1974). [A3]

### 3.6 REPORTS NOT REVIEWED

D'Alessandro, F., et al., Airport Surface Traffic Control Concept Formulation Study: Operations Analysis of O'Hare Airport, Part I, Report FAA-RD/TXC-75-120-3, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, July 1975. [A3]

Harrison, R.N., "ATC Simulation at London Airport," Aircraft Engineering, pp. 4-5 (March 1974). [A3]

#### 4. MODELS OF TERMINAL AIRSPACE (CATEGORY A4)

Models reviewed in this category are concerned with air traffic operations in the terminal area. We can distinguish two broad model categories based on the models' scope.

1) Performance Models: Models included in this category are primarily designed to evaluate the performance of air traffic control systems in the terminal area under various types of conditions.

2) Optimization-Oriented Models: These include models concerned with optimizing some specific function of the ATC system (for example: path generation and spacing, sequencing of operations, etc.). In most cases these are designed to be interfaced with a performance model for purposes of evaluation.

A listing of Category A4 models reviewed and supporting documents is contained in Section 4.5. Attainability of computer programs for the models in this category is indicated in section 4.6.

##### 4.1 OVERVIEW OF THE MODELS

###### 4.1.1 Performance Models

All the models reviewed here use simulation techniques to analyze the ATC system performance. Simulation is generally considered the best tool for the analysis of complex interactive systems such as the ATC environment in the terminal area. Among the first investigators in this area were Blumstein and later Simpson (see Section 4.4, references 1 and 3). These models have not been reviewed here because, being mostly analytical, they fail to capture the full extent of the interactions present in the ATC environment. It is recommended, however, that the reader begin by studying these models since they provide a basic understanding of the ATC functions and the issues involved in the analysis of air traffic in the terminal area.

The performance models reviewed can be further subdivided into macroscopic and microscopic according to the level of detail included in the simulation. Models in the latter class (Models A4.1, A4.2 and A4.3) "fly" aircraft through terminal airspace by incorporating equations that describe the dynamics of motion of these aircraft. By contrast, macroscopic models (A4.4 and A4.5) represent aircraft as point masses that move between prespecified waypoints in the terminal area according to a set of ATC rules and procedures.

A model developed at the NASA Langley Research Center and at the Research Triangle Institute (Model A4.1) is the most complete and versatile of the microscopic performance models. Its controlling logic simulates current ATC rules and procedures, can run in fast or real-time, and has been extensively used for a variety of purposes. It is therefore recommended for use in detailed performance evaluations of ATC terminal area systems.

Model A4.2 developed at the NASA Ames Research Center is in many ways very similar to A4.1. It incorporates a very particular aircraft sequencing scheme which may be a drawback for some applications. The model has not been extensively tested. In particular, there are indications that high operation rates may adversely affect the model's performance.

The MIT simulation (Model A4.3) is the least complete of the models reviewed since its controlling logic is still under development. It is, however, the most sophisticated of the three microscopic models in its representation of the aircraft dynamic responses and instrument errors as well as other random effects present in the ATC environment. As such, it is a good tool for in-depth research on various controlling strategies (especially strategies which require tight maneuvering). In addition, it is suitable for evaluating the effects of new navigational and surveillance techniques on ATC system performance (safety, capacity, etc.).



The two macroscopic performance models (A4.4 and A4.5) use the techniques of discrete-event simulation, as opposed to continuous-time simulation used by Models A4.1, A4.2 and A4.3. This approach is considerably more economical but the simplifying assumptions are occasionally severe. For certain important terminal area problems (e.g. examination of flight path merging on final approach) use of the macroscopic models is inappropriate. On the other hand, these models are suitable for studies that require only an approximate representation of ATC operations. In such cases, the macroscopic models should enjoy a sizable advantage with respect to computational expense over the microscopic ones. The two macroscopic performance models reviewed are quite similar in many respects. Their use is recommended but interpretation of their results should be done with care, recognizing the models' limitations. Model A4.5, in particular, includes an interesting additional feature in that it is designed to assist in assessing the effects of terminal area facility outages.

#### 4.1.2 Optimization-Oriented Models

These models are concerned with developing new methods of controlling air traffic in the terminal area. Most of the research effort is directed towards automation of the controller's decision-making. The initial attempts towards this goal have used methods from the theory of optimal control. The model proposed by Schmidt and Swaim [A4.6] is typical (and among the best) of a number of models which adopt this approach. This work is, however, primarily of academic interest at this time, since problems of the size commonly encountered in a realistic situation are computationally intractable using the methodology suggested by the model (with today's computer technology).

The other two optimization-oriented models reviewed here take a much less ambitious approach. Parker et al. [A4.7] divide the overall terminal area control problem into three subproblems: (1) optimization of the nominal approach paths; (2) optimization of the path-stretching maneuvers; (3) optimization of the sequencing of runway operations. The models for each of these subproblems are

over-simplified and the contribution to the state of the art in this area is limited.

Tobias [A4.8] formulates the problem of minimizing the time-to-touchdown of each aircraft as a linear program subject to constraints imposed by other traffic currently in the terminal area. His formulation of the constraints is very interesting but this method yields local rather than global optima.

#### 4.2 GENERAL OBSERVATIONS

There is obviously a wide discrepancy between the state of the art of the performance models and that of the optimization-oriented models. Performance models have received considerable attention, understanding of their requirements is good, and existing macroscopic and microscopic models are quite satisfactory in their detailed representation of the terminal area ATC environment. Model A4.1, in particular, has been extensively used with very good results. By contrast, increasing the capacity of a terminal area/airport complex through automation and optimization of the controlling logic is an area of research in which satisfactory results and solutions do not exist at this time. The main reason for this situation is the complexity of the problem. Researchers have only recently begun to realize that suboptimal solutions may indeed be very satisfactory. As a consequence, this area remains wide open, and provides very good ground for further research.

In closing, it should be emphasized that the results (outputs) obtained from the terminal airspace simulation models are very sensitive to the inputs provided by the user. Therefore, in interpreting these results the user should carefully consider the quality and reliability of the inputs. In addition, the results of any simulation should undergo detailed analysis as to their statistical robustness and their statistical significance, before drawing conclusions based on these results.



#### 4.3 CONCLUSIONS AND RECOMMENDATIONS

1. The state of the art of the performance models in this area is satisfactory. Most of the models reviewed are realistic and can produce good and reliable results, if used carefully.
2. The effort required for obtaining results from microscopic performance models is relatively large. It is mostly related to adapting the model to the situation at hand, collecting data, and interpreting the results. The user should, therefore, consider the use of macroscopic models, whenever possible, for obtaining the desired results, and use microscopic models only if the level of detail required dictates such use.
3. The state of the art in optimization-oriented models is not very advanced. For the most part, the models that have been formulated to date make little progress toward obtaining results suitable for practical applications.

#### 4.4 BACKGROUND REFERENCES

1. Blumstein, A., An Analytical Investigation of Airport Capacity, Cornell Aeronautical Laboratory, Report TA 1358-8-1, June 1960.
2. Odoni, A.R., An Analytic Investigation of Air Traffic in the Vicinity of Terminal Areas, MIT, Operations Research Center, Technical Report 46, December 1969.
3. Simpson, R.W., "Analytical Methods of Research into Terminal Area Air Traffic Control Operations," Journal of Aircraft, May-June 1965.

#### 4.5 MODELS REVIEWED AND SUPPORTING DOCUMENTS

##### Model A4.1

Britt, C.L., Jr., et al., Definition of a Terminal Area Air Traffic Model for Studies of Advanced Instrumentation and Control Techniques, Report NASA-CR-111979, National Aeronautics and Space Administration, Washington, DC, December 1971. [A4]

Britt, C.L., Jr., et al., Development of Simulation Techniques Suitable for the Analysis of Air Traffic Control Situations and Instrumentation, Report NASA-CR-112195, National Aeronautics and Space Administration, Washington, DC, December 1972. [A4]

Britt, C.L., Jr., et al., Study of the Impact of Air Traffic Management Systems on Advanced Aircraft Avionic Systems, Report NASA-CR-132278, National Aeronautics and Space Administration, Washington, DC, February 1973. [A4]

Britt, C.L., Jr., et al., Vehicle Dependent Aspects of Terminal Area Guidance and Control, Report NASA-CR-144987, National Aeronautics and Space Administration, Washington, DC, June 1976. [A4]

Britt, C.L., Jr., L. Credeur, C.M. Davis and W. Capron, "Research in Ground-Based Near-Terminal Area 4D Guidance and Control," Paper No. 76-57 in International Congress of Aeronautical Sciences: 10th Congress, Ottawa, Canada, October 3-8, 1976. [A4]

##### Model A4.2

Bernstein, H., A.B. Greenberg, and S. Sokolsky, Terminal Area Air Traffic Control Simulation, Report NASA-CR-152017, National Aeronautics and Space Administration, Washington, DC, September 1976. [A4]

##### Model A4.3

Heinz, V.M., Stochastic Simulation of Terminal Area Airspace, S.M. Thesis (unpublished), MIT Dept. of Aeronautics and Astronautics, Cambridge, MA, September 1976. [A4]



Heinz, V.M., Stochastic Simulation of Terminal Area Airspace: User's Manual, Technical Memorandum, MIT Flight Transportation Laboratory, Cambridge, MA, September 1976. [A4]

#### Model A4.4

Yu, J.C., W.E. Wilhelm, Jr. and S.A. Akhand, "Gasp Simulation of Terminal Air Traffic System," Journal of Transportation Engineering (ASCE), 100, No. TE3, pp. 593-609 (August 1974). [A4]

Yu, J.C. and S.A. Akhand, "Discrete Event Simulation Model of Terminal Air Traffic Control System," in Traffic Control and Transportation Systems: Proceedings of the Second Symposium, Monte Carlo, Monaco, September 16-21, 1974, American Elsevier Publishing Co., New York, NY (1974). [A4]

#### Model A4.5

Greene, L.B., J. Witt and M. Sternberg-Powidzki, User Delay Cost Model and Facilities Maintenance Cost Model for a Terminal Control Area, Volumes I and II: Model Formulation and Demonstration, User's Manual and Program Documentation, Report AAF-220-78-01, U.S. Dept. of Transportation, Federal Aviation Administration Washington, DC, May 1978. [A4].

#### Model A4.6

Schmidt, D.K. and R.L. Swaim, "An Optimal Control Approach to Terminal Area Air Traffic Control," Journal of Aircraft, 10, No. 3, pp. 181-188 (March 1973). [A4]

#### Model A4.7

Parker, S.K., T.A. Straeter and J.E. Hogge, "An Analytic Study of Near Terminal Area Optimal Sequencing and Flow Control," paper No. 12 in Air Traffic Control Systems: AGARD Conference Proceedings, Report CP-105, NATO Advisory Group for Aerospace Research and Development, Brussels, Belgium, June 1973. [A4]

#### Model A4.8

Tobias, L., "Automated Aircraft Scheduling Methods in the Near Terminal Area," Journal of Aircraft, 9, No. 8, pp. 520-524 (August 1972). [A4]

#### 4.6. ATTAINABILITY OF COMPUTER PROGRAMS

Model	Is Computer Program Required?	Program Listing Included In Reviewed Documents?	Program User's Guide Publicly Available?	Can Computer Program Be Readily Written?	Individuals (if known) and Organization to Contact for More Information on the Model
A4.1	Yes	No	Yes	No	C.L. Britt, Jr. Research Triangle Institute Research Triangle Park, N.C. 27709
A4.2	Yes	No	Yes	No	Transportation Group Directorate Energy and Transportation Division The Aerospace Corporation El Segundo, CA
A4.3	Yes	Yes	Yes	No	Robert W. Simpson Room 33-410, MIT Cambridge, MA 02139
A4.4	Yes	No	No	No	Jason C. Yu Dept. of Civil Engineering Univ. of Utah Salt Lake City, Utah
A4.5	Yes	Yes	Yes	No	Kent Haspert ARINC Research Corp. 2551 Riva Road Annapolis, MD 21401
A4.6	Yes	No	No	No	David K. Schmidt School of Aeronautics and Astronautics Purdue University West Lafayette, IN 47907
A4.7	Yes	No	No	No	T.A. Straeter NASA Langley Research Center Hampton, VA. 23365
A4.8	Yes	No	No	No	L. Tobias NASA Ames Research Center Moffet Field, CA 94035

Erzberger, H. and H.Q. Lee, "Optimum Horizontal Guidance Techniques for Aircraft," Journal of Aircraft, 8, No. 2, pp. 95-101 (February 1971). [A4]

Erzberger, H. and H.Q. Lee, Terminal Area Guidance Algorithm for Automated Air Traffic Control, Report TND 6773, National Aeronautics and Space Administration, AMES Research Center, Moffett Field, CA, February 1972. [A4]

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Athans, M. and L.W. Porter, "An Approach to Semi-Automated Scheduling and Holding Strategies for Air Traffic Control," in Proceedings 1971 Joint Automatic Control Conference, Automatic Control Council, Washington University, St. Louis, MO, August 1971. [A4]

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Cohen, S. and F. Maginnis, Statistical Summary of the 1982 Los Angeles Basin Standard Traffic Model, Volumes I and II, Report FAA-RD-73-87, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC April 1973. [A7; A4]

Cohen, S. and F. Maginnis, User's Manual for the Los Angeles Basin Standard Traffic Model, Report FAA-RD-73-88, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, April 1973. [A7; A4]

Faison, W.E., M.B. Meisner and P.H. Petersen, Analytical Study of Air Traffic Capacity in the New York Metropolitan Area and New York Air Traffic Capacity Study (Real Time Simulation), U.S. Dept of Transportation, Federal Aviation Administration, Washington, DC, 1970. [A4]

Gibbar, J.M. and G.E. Lorenz, Simulation of an Air Traffic Control Terminal Area, M.S. Thesis (unpublished), Air Force Institute of Technology, School of Systems and Logistics, Wright-Patterson AFB, OH, June 1977. [A4]



Hildenberger, M., User's Manual for the Los Angeles Basin Standard Traffic Model, Report FAA-RD-73-89, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, May 1973. [A7; A4]

Hsin, C.C., An Analytical Study of Advanced Terminal Area Air Traffic Management and Control, Report R76-13, MIT Flight Transportation Laboratory, Cambridge, MA, September 1976. [A4]

McNamara, J.E., "The Metering System Concept," Journal of ATC, 18, pp. 24-28 (October-December 1976). [A4]

Morgan, H.T. and A.R. Moss, Airspace Configuration and Separation Evaluation-Configuration and Procedures-Terminal ATC Digital Display System Errors, ARTS III: Final Report, Report FAA-RD-76-178, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, 1976. [A4]

Sawyer, R.H. and M.D. McLaughlin, Simulation Studies of STOL Airplane Operations in Metropolitan Downtown and Airport Air Traffic Control Environments, Report NASA TN-D-7740, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, 1974. [A4]

Wilhelm, W.E. and J.W. Schmidt, "A View of Air Traffic Control in Future Terminal Areas," Journal of Aircraft (London), pp. 366-372 (January 1973). [A4]

#### 4.8 REPORTS NOT REVIEWED

Hart, S.G., D. McPherson, J. Kreinfeldt and T.E. Wemple, Multiple Curved Descending Approaches and the Air Traffic Control Problem, National Aeronautics and Space Administration, NASA Ames Research Center, Moffett Field, CA, August 1977. [A4]

Maurer, J., P.J. O'Brien and W. Crimbring, Preliminary Two-Dimensional Area Navigation Terminal Simulation, Report FAA-NA-74-16, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, 1975. [A4]

Mohleji, S.C. and B.M. Horowitz, Metering and Spacing System Simulation of Terminal Arrivals at Denver's Stapleton Airport, Report MTR-6327, The MITRE Corporation, McLean, VA, 1973. [A4]

U.S. Dept. of Transportation, Selected Documents for Aviation Planning in the Terminal Area, Report FAA-ASP-76-3, Federal Aviation Administration, Washington, DC, 1976. [A4]

## 5. MODELS OF AIR ROUTE TRAFFIC (INCLUDING ATC COMMUNICATIONS) (CATEGORY A5)

Models in this category are concerned with various aspects of air traffic activity during the en route phase of flight, i.e. while aircraft fly through individual sectors of Air Route Traffic Control Centers (ARTCC's). Unlike the terminal area, during this phase of flight aircraft fly along constant-altitude, straight-line paths for extended periods of time. Consequently, it is relatively easy to develop models, i.e. idealized representations of air traffic activity in isolated parts of en route sectors, by focusing on air route segments or on specific air route intersections. By contrast, the modeling of a network of air routes (or of a group of sectors) is a considerably more complicated task. Models of this latter type are reviewed in Section 7.

Category A5 also includes models of ATC communications. This choice was made because the communications models reviewed were developed primarily with reference to air route traffic. However, the same communications models can be applied, with some adjustments, to terminal area ATC communications as well.

A list of Category A5 models reviewed and supporting documents is contained in Section 5.3. Attainability of computer programs for models in this category is indicated in Section 5.4.

### 5.1 OVERVIEW OF THE MODELS

#### 5.1.1 Air Route Capacity Models

The air route capacity models reviewed here (Models A5.1, A5.2, and A5.3) are all analytical (as opposed to "simulations") and follow similar approaches. Air route capacity is determined by computing two quantities: the capacity of the straightline segments of air routes which lie between air route intersections; and the capacity of the intersections themselves.



W. Siddiquee has developed simple mathematical expressions for both of the above quantities in work performed at the Stanford Research Institute (Models A5.1 and A5.2). With regard to straight-line air route segments the fundamental idea is the following (Model A5.2): if all aircraft on a given air route move at the same constant speed of  $V$  knots, and if the minimum longitudinal separation between successive aircraft on the route is  $X$  nautical miles, then the route's capacity is given by  $V/X$  aircraft per hour (since aircraft are spaced by  $X/V$  hours, at minimum spacing). If several classes of aircraft are present - with different classes characterized by different speeds - then the slowest aircraft will be the ones that determine the capacity of the route, unless some passing ("overtaking") of slow aircraft by fast ones is permitted. Thus, the expression for the straight-line segment capacity that Model A5.2 finally develops is a function of (1) the hourly flow rates and speeds of different classes of aircraft on an air route, (2) the length of the (uninterrupted) air route, (3) the minimum longitudinal separation requirements on the air route, and (4) the maximum permissible number (if any) of overtakings per hour on that route.

Following an identical line of reasoning, Model A5.1 is based on the observation that when an aircraft on air route A (for example) crosses an intersection of A with another air route, B, then the flow of traffic on B must be interrupted ("blocked") for a certain interval of time. This blockage time depends on the speed of the aircraft on air route A, the minimum ATC longitudinal and lateral separation requirements between aircraft en route, and the size of the angle between the two air routes, A and B, at the intersection. Thus the final expression developed in Model A5.1 for intersection capacity depends on (1) the average flow rate per hour of aircraft and the speed of aircraft along each of the two intersecting routes, (2) the angle of intersection, (3) the lateral and longitudinal ATC separation requirements, and (4) the maximum permissible number (if any) of intersection ("crossing") conflicts per hour at that point.

Model A5.3 (due primarily to W. Dunlay) is essentially an extension and generalization of Models A5.1 and A5.2. It was developed as a safety model but can be used, as well, as an air route capacity model. For instance, whereas Models A5.1 and A5.2 postulate that the flow of aircraft of each speed class is uniform along each route (i.e. the aircraft are spaced equally), Model A5.3 assumes random spacings (using a Poisson model). In addition, Model A5.3 generalizes the intersection problem to the case where any specified number of air routes (not restricted to just two) intersect at any particular point. Another contrasting feature of Model A5.3 is its "probabilistic" nature, in the sense that it takes into account the probability that any particular pair of aircraft classes will meet at an intersection or will be on successive positions on a straight-line track. Since Model A5.3 is developed under a more general (albeit still simplified) set of assumptions, it can be viewed as superseding Models A5.1 and A5.2. Model A5.3 is also reviewed under Category B1.

In the absence of any other constraints (such as excessive communications delay or controller workload), these capacity models are quite adequate for providing satisfactory estimates of the number of aircraft per hour that can traverse a single air route, or pass through an air route intersection.\*

Two additional observations are in order. First, the term capacity, as used in Models A5.1 A5.2 and A5.3, signifies the "maximum throughput" rate at the air routes, exactly like the definition of capacity used for runways (see Section 1.1). Therefore, the estimated capacities are not based on a concept of "acceptable levels" of delay. Second, one should keep in mind that these models were developed in the context of research projects which were mainly concerned with controller workloads, and with controllers' perceptions of potential ATC

\*Even some of these constraints can be taken into account by placing upper limits on the capacities of air routes and intersections as dictated by such constraints.

conflicts on air routes. Thus, the emphasis in the models is on producing estimates of the number and duration of overtaking and crossing conflicts as a function of traffic density, traffic characteristics and air route geometry. These estimates are, in turn, "fed into" controller workload models (see Section 6) to obtain sector capacities and manning requirements for sectors.

#### 5.1.2 ATC Communications Models

The ATC communications models reviewed here are intended to represent the pilot/controller voice communications process with regard to characteristics such as communications channel utilization and communications delays. A delay in this case is the amount of time that a pilot or a controller may have to wait, due to high channel utilization, to obtain access to the channel. Thus, for the frequency used by each sector, the voice communications channel is viewed as a service system with "customers," i.e., radio messages, competing for access to it. Full utilization of the service unit in this context would mean that radio messages are being transmitted without a respite, for almost 100 percent of the time (allowing only for the minimum possible intervals between a pilot's message and the controller's response to it).

The first of the models reviewed, Model A5.4, applies classical queueing theory to the ATC communications problem. A sector is viewed as a queueing system that can accommodate a finite number of aircraft simultaneously. (If excessive demand materializes, aircraft must wait in holding patterns within or outside the sector.) The aircraft within a sector act as generators of demand (i.e., of radio messages) for a second queueing system - which is the communications channel. Thus we have one queueing system "feeding" another one, hence, the appellation "nested queues" used to describe the model. Unfortunately, in order to fit the available mathematical expressions from queueing theory, several questionable assumptions are made in connection with Model A5.4 (see detailed review in Part III). Hence, while it may provide adequate approximations for certain cases, Model A5.4 is not recommended for general use.



Model A5.5, by contrast, is a simulation model of ATC communications that has been developed with great attention to detail over a five-year period at Princeton University with support from NAFEC (Atlantic City, New Jersey). Conceptually, the model is a simple one, simulating the communications channel as a single-server queueing system. Radio messages of (probabilistically) varying length act as the "customers" of the system, with one message at a time occupying the channel. A high degree of realism is achieved by using inputs which were developed after careful statistical analysis of a very extensive set of data collected at the New York ARTCC in 1969. Furthermore, the model has been validated with data from the Houston ARTCC. The validation analysis is exemplary in its thoroughness and in the sophistication of the statistical techniques that it uses. Indeed, it would be fair to say that, of all the models reviewed in this report, Model A5.5 stands out with regard to both preparation of model inputs and validation of model results. In fact, it is the only model that can be considered as truly validated. Thus, in addition to its merits as an analysis tool for problems related to ATC voice communications, this model is strongly recommended to ATC professionals as a fine example of what model development should ideally be like.

## 5.2 CONCLUSIONS AND RECOMMENDATIONS

Our principal conclusions with respect to Section 5 can now be summarized as follows:

1. The existing analytical models seem adequate for estimating single air route capacity and air route intersection capacity. The geometry and the "physics" of the situations that these models depict and analyze are very simple. Model A5.3 is the most general one in this area and contains the least restrictive set of assumptions.

2. The capacity models referred to above constitute important intermediate steps in estimating controller workload. Estimates of the number and duration of crossing and overtaking

conflicts obtained through these models are used as inputs to models used for estimating controller workload (see Section 6).

3. An outstanding simulation model of ATC voice communications has been developed by Princeton University with support from NAFEC. The model is exemplary with regard to both preparation of model inputs and validation of model results. Its use is strongly recommended.

### 5.3 MODELS REVIEWED AND SUPPORTING DOCUMENTS

#### Model A5.1

Siddiquee, W., "A Mathematical Model for Predicting the Number of Potential Conflict Situations at Intersecting Air Routes," Transportation Science, 7, No. 2, pp. 158-167 (May 1973).

[B1; A5, A6]

Siddiquee, W., "A Mathematical Model for Predicting the Duration of Potential Conflict Situations at Intersecting Air Routes," Transportation Science, 8, No. 1, pp. 58-64 (February 1974).

[B1; A5, A6]

#### Model A5.2

Siddiquee, W., Computer-Aided Traffic/Airway/VOR(TAC) Network Methodologies, Volumes I and II, Report FAA-RD-72-118, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, August 1972. [A5; A6, B1]

Siddiquee, W., "Air Route Capacity Models," Navigation, 20, No. 4, pp. 296-300 (Winter 1973-74). [A5; A6, B1]

#### Model A5.3

Dunlay, W.J., Jr., R. Horonjeff and A. Kanafani, Models for Estimating the Number of Conflicts Perceived by Air Traffic Controllers, Special Report, University of California at Berkeley, Institute of Transportation and Traffic Engineering, Berkeley, CA, December 1973. [B1; A5, A6]

Dunlay, W.J., Jr. and R. Horonjeff, "Applications of Human Factors Data to Estimating Air Traffic Control Conflicts," Transportation Research, 8, No. 3, pp. 205-217 (August 1974). [B1; A5, A6]

Dunlay, W.J., Jr., "Analytical Models of Perceived Air Traffic Control Conflicts," Transportation Science, 9, No. 2, pp. 149-164 (May 1975). [B1; A5, A6]

Schmidt, D.K., "On the Conflict Frequency at Air Route Intersections," Transportation Research, 11, No. 3, pp. 351-355 (August 1977), [B1; A5, A6]

#### Model A5.4

Modi, J.A., "A Nested Queue Model for the Analysis of Air Traffic Control Sectors," Transportation Research, 8, pp. 219-224 (August 1974). [A5]

#### Model A5.5

Hunter, J.S., D.E. Blumenfeld and D.A. Hsu, Modeling Air Traffic Performance Measures, Volume I: Initial Data Analyses and Dictionaries, Volume II: Initial Data Analyses and Simulations, Report FAA-RD-73-147-I and II, U.S. Dept. of Transportation Federal Aviation Administration, Washington, DC, July 1974. [A5]

Hunter, J.S. and D.A. Hsu, Simulation Model for New York Air Traffic Control Communications, Report FAA-RD-74-203, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, February 1975. [A5; A7]

Hunter, J.S. and D.A. Hsu, Applications of the Simulation Model for Air Traffic Control Communications, Report FAA-RD-76-19, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, February 1977. [A5; A7]

Hsu, D.A. and J.S. Hunter, "Analysis of Simulation-Generated Responses Using Autoregressive Models," Management Science, 24, No. 2, pp. 181-190 (October 1977). [A5]

Mulholland, R., Simulation Model for Air Traffic Control Communications, Report FAA-NA-76-30, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, July 1977. [A5]



#### 5.4. ATTAINABILITY OF COMPUTER PROGRAMS

Model	Is Computer Program Required?	Program Listing Included in Reviewed Documents?	Program User's Guide Publicly Available?	Can Computer Program be Readily Written?	Individuals (if known) and Organization to Contact for More Information on the Model
A5.1	No	No	No	Yes	Robert Ratner Stanford Research Institute Menlo Park, CA 94025
A5.2	No	No	No	Yes	Robert Ratner Stanford Research Institute Menlo Park, CA 94025
A5.3	No	No	No	Yes	William J. Dunlay Peat, Marwick, Mitchell and Co. San Mateo, CA. P.O. Box 8007 San Francisco International Airport San Francisco, CA 94128
A5.4	Yes	No	No	Yes	J.A. Modi Research Triangle Institute Research Triangle Park, NC 27709
A5.5	Yes	Yes	Yes	No	Robert G. Mullholland Federal Aviation Administration NAFEC Atlantic City, N.J. 08405

## 5.5 OTHER RELATED REPORTS

Braff, R. and S. Mohleji, Analysis of Route Widths in the Domestic Airspace, Report M63-226, The MITRE Corporation, McLean, VA, November 1973. [B1; A5]

Dunlay, W.J., Jr., A Stochastic Model of Controlled Airway Traffic, Report FAA-AV-71-6, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, D C , September 1972. [B1; A5, A6]

Hoffman, W.C., W.M. Hollister and K.R. Britting, North Atlantic Aided Inertial Navigation System Simulation, Volume I: Technical Results, Report FAA-RD-73-112, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, 1973. [A5; B1]

Kaatz, L.M., A Simulation and Queueing Model for the Study of En Route Air Traffic Systems, Report INS-Research Contribution 169, Institute of Naval Studies, Center for Naval Analyses, Arlington, VA, 1971. [A5]

Ohman, M. and R.F. Irwin, A Compendium of NAS En Route System Performance, Analysis, and Modeling Documentation Relative to the Model A3D2 En Route Operational System-Final Report, Report FAA-RD-76-175, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, 1976. [A5]

Wilson, J.G., "ATC Research-Simulating Arrival/Tower Communications," Journal of CATCA (Ottawa), 4, No. 2, p. 12 (Fall 1972). [A5]

Wilson, J.G., "Simulating Arrival-Tower Communications," Journal of ATC, 14 (November 1972). [A5]

#### 5.6 REPORTS NOT REVIEWED

Behnham, A., A. Hatch and S. Dass, Airspace Control Environment Simulator-Final Report, Report on file at U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, December 1971. [A5; A6]

Czech, H.C., Automatic Generation of Traffic Samples for Real-Time ATC Simulations, Report 62, Eurocontrol, Brussels, Belgium, April 1973. [A5]

Francis, G.H., VHF Channel Allocation in Relation to Air Traffic Density and Controller Workload, Report ATCEU 291, RAF Farnborough Hants, United Kingdom, 1968. [A5; A6]

Lefferts, R.E., Performance Results of Model 3D1 Surveillance Simulation, Report MTR-446S54, The MITRE Corporation, McLean, VA, 1973. [A5]

Miller, H.G., Analysis of En Route Metering Concepts, Report MTR-7002, The MITRE Corporation, McLean, VA, August 1975. [A5]

Nepveu de Villemarceau, G. and J.M. de Raffin-Dourney, "The Concept of Capacity," Revue du S.G.A.C., May 1973. [A5]

Purcell, P.R., Procedure for Simulating Any ARTCC on the En Route SSF Via Adaptation, Report MTR-4253, The MITRE Corporation, McLean, VA, 1975. [A5]



## 6. CONTROLLER WORKLOAD AND PERFORMANCE MODELS (CATEGORY A6)

This category is concerned with modeling the workload of ATC controllers (human); or more precisely, the workload of a man-machine control position in an ATC control sector.

A listing of Category A6 models reviewed and supporting documents is contained in Section 6.4. Attainability of computer programs for the models in this category is indicated in Section 6.5.

### 6.1 GENERAL OBSERVATIONS

The state of the art in Human Factors research at the present time is such that it is difficult even to define, with any precision, what is meant by workload, particularly as it concerns mental workload. As we introduce automation in the form of computers and displays, the controller's work undergoes transition from physical control activities (which are observable) to supervisory of monitoring activities of a mental nature (which cannot be completely observed and measured). Most of the models described here have an empirical base of measured completion times for well-defined, observable tasks in the current ATC semi-automated man-machine environment. Thus, they are normative models which do not account for any variation in individual controller capability. They might better be described as "taskload" models which produce overall average measures of taskload by summing the average contributions from many small tasks which occur in response to traffic flow rates in the ATC sector.

Following the original modeling performed by Arad (Model A6.1), ATC controller work is classified as "routine," "conflict," and "surveillance." Routine work describes the processing of an aircraft which would occur even if there were no other aircraft present. It is presumed to vary directly with traffic flow rate. Conflict work describes the prediction and resolution of potential

aircraft collisions. It is presumed to vary with the square of traffic flow rate. Today it would be described as separation assurance work. Finally, surveillance work has been identified in recognition of the fact that the radar controller devotes much of his attention to monitoring the radar display. It is presumed to vary with the average number of aircraft in the sector. This last category is an example of mental work which is difficult to observe or measure.

The models reviewed here all postulate the occurrence of "events" caused by the flow of traffic in the sector. The prediction of "event frequency" as a function of traffic flow rate is a common, necessary step in all the models. This depends on the type of sector (en route high altitude, terminal transition, etc), the sector geometry (number of intersections, etc.), and the mix of traffic with respect to altitudes, speeds, etc. Models which generate "conflict events", described in Sections 5 (Air Route Traffic) and 8 (Safety), are used as inputs to these controller workload models.

Most of the models associate a set of controller "tasks" with each "event" and, using an empirical basis, develop a measure of work for each task. By estimating the event frequency for a given traffic flow rate, the total work rate, called "workload," is developed as a function of traffic flow rate.

Following this, a subjective assessment of maximum traffic flow for a sector is obtained from one or more experienced controllers (notice that this judgement depends upon their skills). This assessment is used to establish a maximum workload value for the sector, and for other sectors. If this provides a consistent maximum value across sectors, it is taken as the capacity of a known controller (or control team). If relatively small changes are made in the sector in the form of staffing, procedures, automation, geometry, etc., it may be possible to estimate a new taskload as a function of traffic flow rate and, consequently, a new value of the capacity of a sector, in terms of aircraft per hour. It would be highly questionable to use these empirically-based

models to estimate workload or capacity for radical changes in sector or control position activities.

## 6.2 OVERVIEW OF MODELS

### 6.2.1 Model A6.1 - Arad's Model

This model, developed in 1964 by the Systems Design Team of Project Beacon, is reviewed here because it is the origin of the methods followed by subsequent models. Arad classifies controller's workload as background, routine, and airspace. Background work is assumed to be constant, routine work is assumed to vary in proportion to traffic flow rate, and airspace work is assumed to vary in proportion to the square of the traffic flow rate. Thus,

$$WL = K_0 + K_1 \cdot F + K_2 F^2 \quad (1)$$

Where WL = workload measured in DEW (Dynamic Element of Work) per hour

F = traffic flow rate in sector (aircraft per hour)

$K_0$  = background work coefficient (DEW per hour)

$K_1$  = routine work coefficient (DEW per aircraft)

$K_2$  = airspace work coefficient (DEW per aircraft per aircraft/hour).

The model defines six kinds of ATC events as routine work. An average work rating (measured in DEW's) was determined subjectively by interviewing a large number of controllers. The event frequency for a given sector is observed, and used to obtain a value for routine workload, measured in DEW per hour, called DEL (Dynamic Element of Load). Then, given the sector geometry, traffic mix, etc., a model for the frequency of occurrence of crossing or overtake conflicts (see also Sections 5 and 8) is established as a function of general sector characteristics. A value for work per conflict was also established, subjectively, by interviews with 280 controllers. It was decided that  $K_0 = 0$ , i.e., background work was so insignificant that it could be ignored.



Arad did not attempt to establish a sector capacity or workload maximum. Jolitz (See Section 6.7) used this model in a field verification study, which obtained controller subjective assessments of workloads. He found that controller assessments were strongly correlated to the average number of aircraft present in a sector and not to the flow rate, F,. This finding has also been reported by Pasmooij, et al., (see Section 6.6).

#### 6.2.2 Model A6.2 - TRW Model

This model is different from the other models of this section in that it is based on a large-scale simulation model which could represent the dynamic operation of multiple sectors of some portion of the ATC system. Traffic flow is generated by specifying a large number of 4-D flight plans for aircraft which are automatically controlled by a separation assurance algorithm en route, and a rudimentary metering and spacing algorithm in the terminal areas. The occurrence of ATC tasks is dynamically generated by running the simulation model, as distinct from the static analytical methods of other models.

There are 17 functions and 165 tasks defined in this model. Each task is assigned to a man or machine at a control position as it dynamically occurs in the simulation. Each task is described by a distribution of task times, and a priority ranking by comparison with other tasks. It is not clear that a data base on task times was gathered from field surveys.

The measure of workload used in this model is simply the "busy time," i.e. the percentage of time a man or machine is busy working on assigned tasks during the simulation run. With this measure, the implicit definition of capacity is a sector workload value of 100 percent. The model does not appear to have had any applications or validation testing.

#### 6.2.3 Model A6.3 - Schmidt's Model

This model is a simple version of the RECEP model (Model A6.4) which follows, and is completely superseded by the more

extensive applications and supporting data base of that model. It may be best to regard it as an application of RECEP. This model creates five categories of "routine" events and two categories of "conflict" events. Event processing times were obtained from field surveys, and the minimum times to process each event are used as a measure of workload. Relative event frequencies (average events per aircraft) for routine events are gathered from field observation of the sector, and analytical conflict models (identical to those used in RECEP) are used to generate conflict events as a function of traffic flow.

In this model workload measures are normalized so that they give a value of 100 at capacity workload. Controller subjective assessments of capacity were gathered and, using this data, the workload coefficients (originally based on minimum processing times) were adjusted. The resulting values were called CDI (Control Difficulty Index). This normalization procedure seems very useful, but was not adopted by RECEP.

#### 6.2.4 Model A6.4 - RECEP

RECEP (Relative Capacity Estimating Process) represents the result of several years of research work by the Stanford Research Institute. It clearly represents the current state of the art in this area, and has demonstrated its usefulness in a number of problem areas.

The RECEP model creates six categories of "routine" ATC events (General, Traffic Structuring, Pointout, Handoff, Coordination, and Pilot Request), each of which have various numbers of subevents (6, 12, 3, 7, 6, and 9 respectively) for a total of 43 ATC events. Each routine event has associated with it tasks from a total of five categories (Air/Ground Communication, Flight or Radar Data Processing, Interphone Communication, Flight Strip Processing, Intrasector Voice Communication). By summing minimum task times for the tasks associated with each event, a minimum event time is obtained. By observing the event frequency (events/aircraft) for a variety of types of sectors, a "routine" workload

coefficient (man-seconds/aircraft) can be estimated. The routine workload is then obtained in man-seconds, as directly proportional to the sector traffic flow. This is estimated for the sector team, and also for the radar controller position in the sector.

"Conflict" workload is estimated by using conflict generation models (see Section 5) for every intersection and airways segment in the sector. This generates frequency of occurrence of conflict events in the sector as a function of traffic flow. Data gathered in the field by video tape playbacks and controller interviews provided estimates of 60 work-seconds per crossing conflict and 40 work-seconds per overtake conflict. In this manner, the conflict workload for the sector (or radar controller) can be estimated.

RECEP introduces "surveillance" workload in recognition of the fact that the radar controller is working as he monitors the radar display. It is estimated simply by using a surveillance workload coefficient value of 1.25 work-seconds per aircraft-minute, which was obtained from interviews with controllers. This work is proportional to the average number of aircraft under surveillance, and thus to sector size as well as to traffic flow rate.

The sum of these three workload components gives a team (or radar position) workload measured in work-minutes per hour. Again, by means of interviews with controllers, estimates of maximum sector flow rates were obtained, and it was estimated that the work capacity of a radar controller is 48 work-minutes per hour, and that of a sector team is 66 work-minutes per hour. These estimates lack precision and do not account for the variations which seem to occur among individual controllers.

The RECEP model is very detailed. It probably should only be used by analysts who are very familiar with its construction and data base, and who, therefore, can correctly extend it to new application areas. It is not clear how great a deviation from current sector operations can be safely accommodated by the model.



This model has a bias towards estimating sector capacity rather than workload. It would be interesting to correlate its workload values in work-seconds per hour with subjective assessments of workload obtained from controllers using the WorkPace methodology mentioned in the reference for Model A6.4 (see Section 6.4)

### 6.3 CONCLUSIONS AND RECOMMENDATIONS

The models reviewed here are normative models which construct an ideal estimate of the taskload at a controller position as a function of traffic.

The RECEP model clearly stands out as the leading model in this area. It depends strongly upon empirical data gathered by field observation of task times, and subjective assessments of sector capacity by controllers. These data are used to calibrate RECEP and make it strongly dependent on current operations. Thus, RECEP is useful in studying incremental changes in today's en route and terminal sector operations. However, it is not clear that it can be applied with confidence to any sector of the ATC system without a prior field survey to obtain data necessary to calibrate the model.

All the models reviewed are based on evaluation of workload associated with identifiable tasks whose execution times can be observed, i.e. physical tasks such as talking, pushing buttons, moving flight strips, etc. As automation is introduced, these physical actions are performed to an increasing extent by machines, and the controller is occupied with mental workload activities such as monitoring and decision making. The introduction of surveillance workload into RECEP shows the difficulty of estimating this type of workload. Values between 1 and 1.5 work-seconds per aircraft-minute were estimated, by controllers, and a middle value of 1.25 was selected. The controller estimates indicate an uncertainty of  $\pm 25$  percent in estimating surveillance workload, and the values are probably only valid for existing ATC procedures and for workload levels such as one encounters at current radar positions. It will be difficult to extend RECEP to more automated sectors, where the human operator will be predominantly occupied with metal workload activities, and will still be the capacity-limiting element of the sector.

#### 6.4 MODELS REVIEWED AND SUPPORTING DOCUMENTS

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Arad, Bar Atid, Notes on the Measurement of Control Load and Sector Design in the En Route Environment, Final Report on Project 102-11 Systems Design Team, Federal Aviation Agency, Washington, DC, June 1964. [A6]

##### Model A6.2

Mertes, F., K. Willis and E.C. Barkley, Automation Applications in an Advanced Air Traffic Management System; Volume VA: Delta Simulation Model-User's Guide; Volume VB: Delta Simulation Model-Programmer's Guide, Report DOT-TSC-OST-74-14, U.S. Dept. of Transportation, Transportation Systems Center, August 1974. [A6]

##### Model A6.3

Schmidt, D.K., "On Modelling ATC Workload and Sector Capacity," Journal of Aircraft, 13, No. 7, pp. 531-537 (July 1976). [A6; A5]

##### Model A6.4

Tuan, P.L., H.S. Proctor and G.J. Couluris, Advanced Productivity Analysis Methods for Air Traffic Control Operations, Report FAA-RD-76-164, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, December 1976. [A6; A7]



# 6.5. ATTAINABILITY OF COMPUTER PROGRAMS

Model	Is Computer Program Required?	Program Listing Included in Reviewed Documents?	Program User's Guide Publicly Available?	Can Computer Program be Readily Written?	Individuals (if known) and Organization to Contact for More Information on the Model
A6.1	No	No	No	Yes	No current information
A6.2	Yes	Yes	Yes	No	F. Mertes TRW Systems Group McLean, VA, 22102
A6.3	Yes	No	No	Yes	David K. Schmidt School of Aeronautics and Astronautics Purdue University West Lafayette, IN 47907
A6.4	No	No	No	Yes	Robert Ratner Stanford Research Institute Menlo Park, CA 94025

## 6.6 OTHER RELATED REPORTS

Brauser, K.J., "Measurements of the Control Capacity of ATC Systems," in Plans and Developments for Air Traffic Systems: Papers Presented at the 20th Symposium of the Guidance and Control Panel, Report AGARD-CP-188, NATO Advisory Group for Aerospace Research and Development, Brussels, Belgium, May 1975.

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Couluris, G.J., R.S. Ratner, S.J. Petracek, P.J. Wong and J.M. Ketchel, Capacity and Productivity Implications of En Route Air Traffic Control Automation, Report FAA-RD-74-196, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, December 1974. [A7; A6, A5]

Dunlay, W.J., Jr. and R. Horonjeff, "Applications of Human Factors Data to Estimating Air Traffic Control Conflicts," Transportation Research, 8, No. 3, pp. 205-217 (August 1974).

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Dunlay, W.J., Jr., "Analytical Models of Perceived Air Traffic Control Conflicts," Transportation Science, 9, No. 2, pp. 149-164 (May 1975). [B1; A5, A6]

Pasmooij, C.K., C.H.J.M. Opmeer, and B.W. Hyndman, "Workload in Air Traffic Control," in Monitoring Behavior and Air Traffic Control, NATO Conference Series III, Plenum Press, March 1976.

[A6]

Ratcliffe, S., "Mathematical Models for the Prediction of Air Traffic Controller Workload," The Controller, 11 (December 1972).

[A6]

Siddiquee, W., "A Mathematical Model for Predicting the Number of Potential Conflict Situations at Intersecting Air Routes," Transportation Science, 7, No. 2, pp. 158-167 (May 1973).

[B1; A5, A6]

Siddiquee, W., "Air Route Capacity Models," Navigation, 20, No. 4, pp. 296-300 (Winter 1973-74). [A5; A6, B1]

Siddiquee, W., "A Mathematical Model for Predicting the Duration of Potential Conflict Situations at Intersecting Air Routes," Transportation Science, 8, No. 1, pp. 58-64 (February 1974). [B1; A5, A6]

Smith, A.D.N. and R.G. Stamp, A Method for Estimating the Capacity of Air Traffic Sectors from Observation of Control Workload, Paper 75041, Civil Aviation Authority, United Kingdom, August 1975. [A6]

Wong, P.J., G.J. Couluris and D.K. Schmidt, "Aggregate Flow Model for Evaluating ATC Planning Strategies," Journal of Aircraft, 14, No. 6, pp. 527-532 (June 1977). [A7; A6]

Yu, J.C. and S.A. Akhand, "Discrete Event Simulation Model of Terminal Air Traffic Control System," in Traffic Control and Transportation Systems: Proceedings of the Second Symposium, Monte Carlo, Monaco, September 16-21, 1974, American Elsevier Publishing Co., New York, NY (1974). [A4]

Yu, J.C., "Quantification of Air Traffic Controller's Acceptable Workload," The Controller, 14. (May 1975). [A6]



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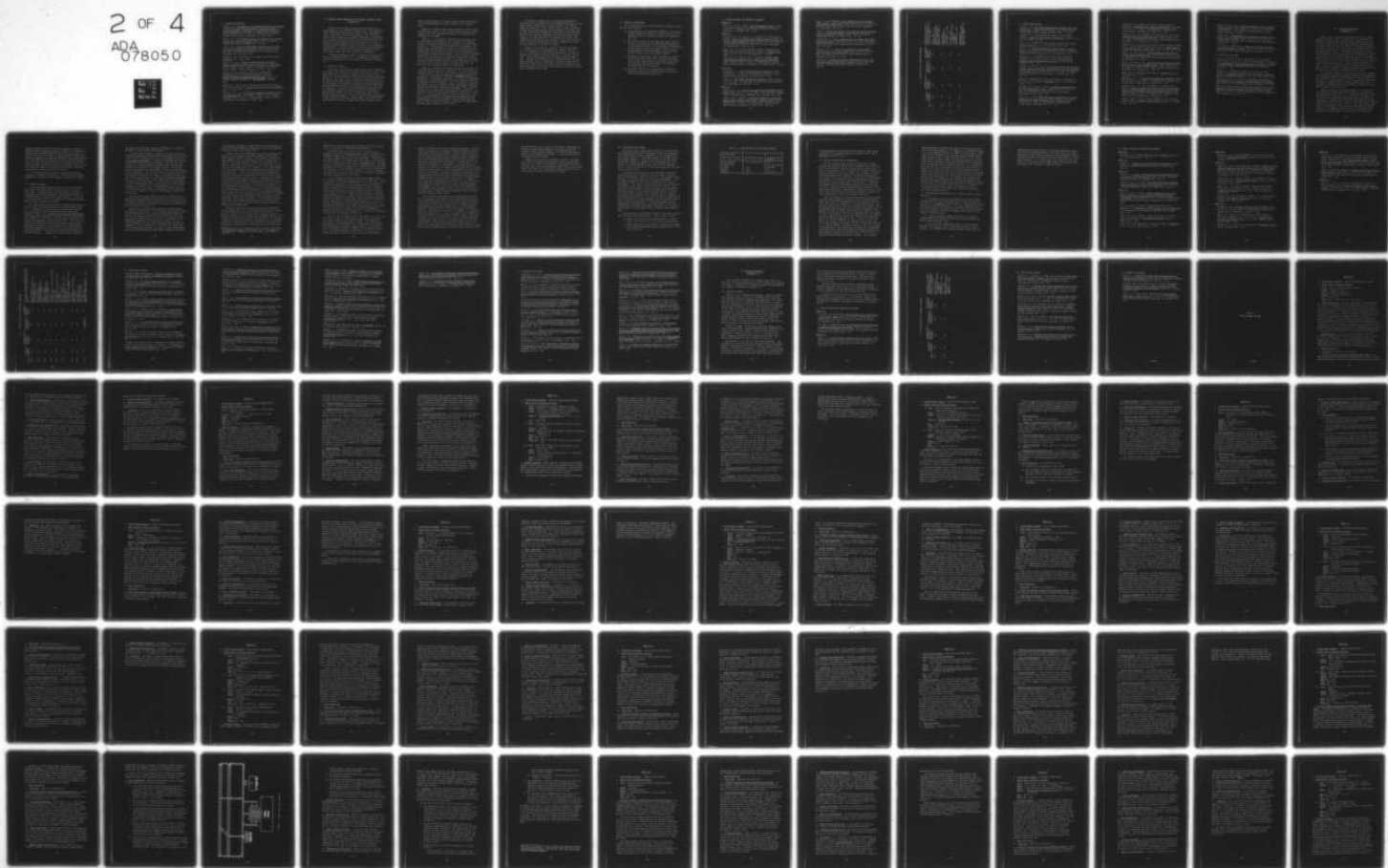
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Francis, G.H., VHF Channel Allocation in Relation to Air Traffic Density and Controller Workload, Report ATCEU 291, RAF Farnborough Hants, United Kingdom, 1968. [A5; A6]

Jolitz, G.D., Evaluation of Mathematical Model for Use in Computing Control Load at ATC Facilities, Report SRDS RD-65-69, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, June 1965. [A6]

Kalsbeck, J.W.H., "Standards of Acceptable Load on ATC Tasks," Ergonomics, 14 (1971). [A6]

Kuhar, W.T. et al., Impact of Automation upon Air Traffic Control System Productivity/Capacity (ARTS-III): Final Report, Report FAA-RD-77-39, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, 1976. [A6; A5]

Leplat, J. and A. Bisserot, "Analysis of Information Processing at the Air Navigation Controller Station," Bulletin d'Etudes et Recherches Physologiques, 14, No. 1-2 (1965). English translation in The Controller, 5 (1966). [A6]

Ratcliffe, S. and H. Gent, "The Quantitative Description of a Traffic Control Process," Journal of the Institute of Navigation, 27, No. 3 (July 1974). [A6]

Rossiter, S., et al., The Controller/Computer Interface with an Air-Ground Data Link, Final Report, Volumes I and II, Report FAA-RD-75-133, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, 1975. [A6]

## 7. MODELS OF MAJOR SEGMENTS OF THE NATIONAL AIRSPACE SYSTEM (CATEGORY A7)

Models in this category are concerned with operations in major segments of the National Airspace System. These models cut across the airport/terminal area/en route sector geographical lines, unlike the models we have examined so far. Typically, a model in this category would examine, simultaneously, operations at an ensemble of airports and air route sectors and would, for instance, be concerned with how aircraft delays at any given airport propagate through the other airports in the system under consideration. To the ATC planner such models are particularly important since, ideally, they can provide information about system-wide (rather than local) measures of performance.

A listing of Category A7 models reviewed and supporting documents is contained in Section 7.3. Attainability of computer programs for the models in this category is indicated in Section 7.4.

### 7.1 OVERVIEW OF MODELS

A relatively small number of models that could be considered to belong to this category were identified during our review. The main reason for the scarcity of models in this category would appear to be the high degree of difficulty associated with setting up models of this type. Due to the large size and complexity of any network that would purport to represent realistically any non-trivial segment of the National Airspace System, model designers must make difficult choices as to the degree of detail they wish to incorporate. Too little detail would seriously detract from the potential usefulness of the model, while too much detail would lead to a model size which is impractical, even for the largest available computers. The net result of these difficulties is that, while there have been several papers which describe the specifications of would-be simulations of large segments of the



ATC system (see Section 7.4- Bales, Burford, Davis and Medeiros), very few implementations of these concepts seem to actually exist.

Models A7.1 and A7.2, which are reviewed here, offer a clear contrast with respect to level of detail chosen, and are a good illustration of how important this choice is to the practical usefulness of the models.

Model A7.1 is a simulation designed by the Autonetics Division of Rockwell International, and is capable of simulating aspects of National Airspace System operations to a minute level of detail. A network structure is used in the simulation, with network nodes corresponding to airports or to intersection and merging points of air routes, and network arcs representing air route segments connecting these nodes. Despite several simplifying assumptions, the model pays a heavy price for its high level of detail. Providing appropriate inputs to the model is a difficult and time-consuming process, and only very limited aspects of the ATC system can be simulated before the model exceeds its own array-size limitations and memory-size limitations.

Model A7.2, developed by the Stanford Research Institute, is a much more macroscopic one by comparison. It, too, is based on a network structure, but the level of detail does not exceed what is necessary to develop some approximate, aggregate measures of performance. These measures, moreover, are derived from aggregate mathematical relationships rather than from a detailed simulation of individual aircraft movements. Thus, for instance, controller workload in a sector is established from a mathematical relationship between controller workload and the total "flow" of aircraft through a sector (rather than by simulating how a controller interacts with each of the aircraft present in the sector). While Model A7.2, in its present state, can only be viewed as a "first cut" at the development of techniques for modeling multisector ATC operations, it is the assessment of the reviewers that the model is highly promising and that it stands out in comparison to the other models reviewed in this section.

The objective of Model A7.3 is to develop techniques for analyzing airport interactions and for examining how delays at one airport affect flight delays at other airports. Two types of delays are identified: type A delays which are those suffered by a flight during the departure and arrival phases of a flight leg; and type B delay which propagates through the air transportation network due to late gate departures by delayed aircraft. Unfortunately, the Airport Network Flow Simulator uses rather crude techniques for estimating Type A and Type B delays and its results cannot, therefore, be considered reliable. However, this model also has potential for further development.

Finally, in this Section, we review a body of work (Model A7.4) which has led to the development of typical "scenarios" (i.e. of "snapshots" of peak instantaneous traffic) for the Los Angeles area airspace at various time periods (1972-73, 1982-83, 1995). These scenarios have been recorded on computer magnetic tape. Although the "snapshots" do not constitute models (in the sense that they do not, by themselves, lead to any analytical or simulation results) they do provide a convenient testbed for terminal area and en route traffic studies and are, therefore, brought to the attention of the reader.

## 7.2 PRINCIPAL CONCLUSIONS

The principal conclusions from the reviews of models in this Section are as follows:

- a) Integrated models of significant segments of the National Airspace System are difficult to develop and, as a consequence, there is a relative scarcity of such models at this time.
- b) The crucial decision in developing such models concerns the level of detail that the model should incorporate. It would appear that due to the complexity of the National Airspace System, macroscopic models are more likely to be computationally and analytically viable given the present state of the art in computer science.
- c) An aggregate (macroscopic) model, developed by Stanford Research Institute (Model A7.2), for simulating operations of multi-sector segments of the ATC system seems to be the most useful and reliable of the currently available models in this category.
- d) All models reviewed in this Section are simulation models and they all use a network structure for representing the National Airspace System.



### 7.3 MODELS REVIEWED AND SUPPORTING DOCUMENTS

#### Model A7.1

Chen, C.I. and R.P. Utsumi, Model Documentation Report, Report C73-1218/201, Rockwell International, Autonetics Division, Anaheim, CA , December 1973. [A7]

#### Model A7.2

Couluris, G.J., R.S. Ratner, S.J. Petracek, P.J. Wong and J.M. Ketchel, Capacity and Productivity Implications of En Route Air Traffic Control Automation, Report FAA-RD-74-196, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, December 1974. [A7; A6, A5]

Wong, P.J., G.J. Couluris and D.K. Schmidt, "Aggregate Flow Model for Evaluating ATC Planning Strategies," Journal of Aircraft, 14, No. 6, pp. 527-532 (June 1977). [A7; A6]

Tuan, P.L., H.S. Proctor and G.J. Couluris, Advanced Productivity Analysis Methods for Air Traffic Control Operations, Report FAA-RD-76-164, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, December 1976. [A6; A7]

#### Model A7.3

Bellantoni, J.F., The Airport Network Flow Simulator, Report FAA-ASP-78-9, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, October 1978. [A7]

Gordon, S., The Airport Network Flow Simulator, Report FAA-ASP-75-6, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, May 1976. [A7]

#### Model A7.4

Willett, F.M., Jr., The 1972 Los Angeles Basin Standard Traffic Model, Report FAA-RD-73-90, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, June 1973. [A7; A44]

Cohen, S. and F. Maginnis, Statistical Summary of the 1982 Los Angeles Basin Standard Traffic Model, Volumes I and II, Report FAA-RD-73-87, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, April 1973. [A7; A4]

Cohen, S. and F. Maginnis, User's Manual for the Los Angeles Basin Standard Traffic Model, Report FAA-RD-73-88, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC , April 1973. [A7; A4]

Cohen, S., Statistical Summary of the 1983 Los Angeles En Route Center Standard Traffic Model, Report MTR-6676, The MITRE Corporation, McLean, VA, October 1974. [A7; A5]

Hildenberger, M., User's Manual for the Los Angeles Basin Standard Traffic Model, Report FAA-RD-73-89, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, May 1973. [A7; A4]

Willett, F.M., Jr., The 1973 Los Angeles Air Route Traffic Control Center's Air Traffic Model, Report FAA-NA-74-11, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, 1974. [A7; A5]

Mundra, A.D., Advanced Air Traffic Management System B: 1995 Los Angeles Basin Traffic Model, Volumes I and II, Report No. MTR-6419, The MITRE Corporation, McLean, VA, March 1974. [A7; A4]

#### 7.4 ATTAINABILITY OF COMPUTER PROGRAMS

Model	Is Computer Program Required?	Program Listing Included In Reviewed Documents?	Program User's Guide Publicly Available?	Can Computer Program Be Readily Written?	Individuals (if known) and Organization to Contact for More Information on the Model
A7.1	Yes	Yes	Yes	No	Bernard Gaon Autonetics Division Rockwell International 3370 Miraloma Ave. Anaheim, CA 92803
A7.2	Yes	No	No	No	Robert Ratner Stanford Research Institute Menlo Park, CA 94025
A7.3	Yes	Yes	Yes	No	John Bellantoni U.S. Dept. of Transportation/TSC 55 Broadway Cambridge, MA 02142
A7.4	Yes	No	Yes	No	Richard Harris The MITRE Corporation 1820 Dolley Madison Blvd. McLean, VA 22102



## 7.5 OTHER RELATED REPORTS

- Attwooll, V.W., The Optimum Planning of Air Traffic Flow Under Constraints, Technical Memorandum MATH 7506, Royal Aircraft Establishment, United Kingdom, September 1975. [A7; A5]
- Attwooll, V.W., "Some Mathematical Aspects of Air Traffic Systems," Journal of the Institute of Navigation, 30, No. 3, pp. 394-411 (1977). [A7; A5]
- Bales, G.A., "ASSM-A New Airspace/Airport Simulation Program," Journal of ATC, 16, pp. 13-15 (May-June 1974). [A7]
- Benoit, A., A Survey of Modern Air Traffic Control, Volumes I and II, Report AGARD-AG-209, NATO Advisory Group for Aerospace Research and Development, Brussels, Belgium, 1975. [A7]
- Burford, R.J., "The Application of "Fast-Time" Simulation Techniques to the Study of ATC Systems," The Aeronautical Journal of the Royal Aeronautical Society, 75, pp. 839-845 (December 1971). [A7]
- Condell, H.M. and A.S. Kaprelian, Airline Delay Trends 1973-1974: A Study of Block Time Delays, Ground and Airborne, for Scheduled Air Carriers, Report DOT-TSC-FAA-76-24, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, 1976. [A7; A2]
- Davis, M., "Application of Fast-Time Simulation Techniques to the Study of ATC Systems," Ergonomics, 14, No. 5, pp. 661-668 (1971). [A7]
- De Hollan, A.N. and A.S. Priver, A Conceptual Network Model of the Air Transportation System, Report DOT-TSC-FAA-71-3, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, April 1971. [A7]
- Erwin, R.J., et al., Study and Concept Formulation of a Fourth-Generation Air Traffic Control System, Volumes I-IV, Report on file at U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, 1972. [A7]

Erwin, R.J., M.J. Omoth, W.H. Galer, D. Hartnell and A.L. Yarrington, Strategic Control Algorithm Development, Report DOT-TSC-OST-74-3, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, August 1974. [A7]

Halverson, A.G., F.B. Woodson, R.W. Soper and H.L. Arch, Area Navigation High-Altitude Network Study, Report FAA-RD-76-6, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, D C., February 1976. [A7]

Hoffman, W.C., W.M. Hollister and R.W. Simpson, "Computer Models for Air Traffic Control System Simulation," in Summer Computer Simulation Conference Proceedings, 2, pp. 1107-1120 (1973). [A7]

Hunter, J.S. and D.A. Hsu, Simulation Model for New York Air Traffic Control Communications, Report FAA-RD-74-203, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, February 1975. [A5; A7]

Hunter, J.S. and D.A. Hsu, Applications of the Simulation Model for Air Traffic Control Communications, Report FAA-RD-76-19, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, February 1977. [A5; A7]

Martin, R.W., "Centralized Flow Control," Journal of ATC, 12 (September 1970). [A7]

Medeiros, M.F., Jr., En Route Air Traffic Flow Simulation, Report DOT-TSC-FAA-71-1, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, January 1971. [A7]

Medeiros, M. F., Jr., P.M. MacDonald, V.P. Paglione and R.D. Wright, A Computer Program Functional Design of the Simulation Subsystem of an Automated Central Flow Control System, Report FAA-RD-76-144, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, August 1976. [A7]

Moray, N. and L.D. Reid, "Review of Models of the Air Traffic Control System," Journal of CATCA (Ottawa), 4, pp. 9-14 (Spring 1972). [A7; B1]

Moray, N. and L.D. Reid, A Review of Models of the Air Traffic Control System, Research Report No. 5, University of Toronto/ York University, Joint Program in Transportation, Toronto, Canada, June 1972. [A7; B1]

Ratner, R.S., A Methodology for Evaluating the Capacity of Air Traffic Control Systems, Report FAA-RD-70-69, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, October 1970. [A6; A7]

U.S. Dept. of Transportation, Advanced Air Traffic Management System Study-Technical Summary, Report DOT-TSC-OST-75-6, Transportation Systems Center, Cambridge, MA, March 1975. [A7]

#### 7.6 REPORTS NOT REVIEWED

Ellis, R.S. and R.W. Rishel, "An Application of Stochastic Optimal Control Theory to the Optimal Rescheduling of Airplanes," in Proceedings 1971 Joint Automatic Control Conference, Automatic Control Council, Washington University, St. Louis, MO, August 1971. [A7]

Jackson, A.S., "Modeling Problems in Air Traffic Control Systems," in Mathematical Models of Public Systems, Simulation Council's Proceedings Series, 1, No. 1, pp. 73-86 (1977). [A7]

Paulson, G.A. and V.W. Attwooll, A Technique to Achieve Pre-Planned Balancing of Schedules and Some Results of Its Application, Royal Aircraft Establishment, United Kingdom, 1977. [A7]

Research Triangle Institute, Study of the Impact of Air Traffic Management Systems on Advanced Aircraft and Avionic Systems, Report NASA-CR-132278, National Aeronautics and Space Administration, Washington, DC, 1973. [A7]



## 8. SAFETY-RELATED MODELS (CATEGORY B1)

Models in this category are concerned with safety-related aspects of the ATC system. We define this to mean methods for deriving estimates of the level of safety experienced by users of the ATC system, or for calculating separation standards that will assure that users of the system will experience a prespecified level of safety. We use the term "ATC system" here, in its broadest possible sense: it includes not only those instances (and geographical areas) where surveillance and control services are provided by a ground-based system, but also all those cases where, in the absence of surveillance and control, an air route structure and/or a set of rules and standards exists that provides safety-related guidelines for aircraft flying through the airspace. The latter includes the case of oceanic flying (usually done without the benefit of ground surveillance and control) and VFR flying over the CONUS (Continental United States).

It should be noted that while the above definition includes models designed to evaluate the need for safety-related equipment, or the potential impact of such equipment on aviation safety, it specifically excludes models which are concerned with optimizing the design of specific types of safety-related systems (e.g. airborne or ground-based collision avoidance systems such as the SECANT system or the IPC system).

Another consideration concerning models in this section is the commonality between safety-related measures and controller workload measures (see Section 6). Some models estimate controller workload by calculating, among other things, the number of "conflicts" or hazardous situations that the controller will be called upon to resolve (this is usually expressed as the "expected number of conflicts per unit of time"). Thus, these models have both a safety content (in the sense that the number of possible conflicts is an important indicator of level of safety) and a controller workload content. In such cases the decision on

whether to assign a model to the safety category or to the controller workload category was made on the basis of the degree of emphasis that the model places on each of these two issues. If most of the effort in the model is oriented toward estimating the number of conflicts, the model was assigned to the former category; if, on the other hand, the concern was mostly with what implications the number of conflicts has for the controller, the latter choice was made. Clearly, this process is somewhat arbitrary and the interested reader is advised to review Section 6, for other models which may touch on the area of safety.

A listing of Category B1 models reviewed and supporting documents is contained in Section 8.4. Attainability of computer programs for the models in this category is indicated in Section 8.5.

#### 8.1 OVERVIEW OF MODELS

Several significant efforts in the area of safety-related models have been reported during the time period of interest (1970-1978). It would be fair to state, however, that none of the models reviewed here represent a radical departure from, or a "breakthrough" by comparison to, earlier models. In fact, as will be seen shortly, most of the models are evolutionary developments of models reported in the 1960's.

The safety model which probably has attracted more attention than any other is often referred to as the "Reich model" [Model B1.7]. Although P.G. Reich originally presented the model in 1964 (his Royal Aircraft Establishment reports subsequently appeared as papers in the Journal of the Institute of Navigation - see documents under Model B1.7 in Section 8.4), the model was not fully calibrated, in the sense of having values assigned to its various input parameters, until the late 1960's. This model was extensively utilized in the work of the North Atlantic Systems Planning Group (NAT SPG) in its attempt to set internationally-acceptable standards for aircraft and air route separations over the North Atlantic. In the process, the Reich model underwent some modifications. A summary of its final version, along with

the input values that were used for its parameters, is given by Hershkowitz (see documents under Model B1.7).

The Reich model attempts to estimate, as a function of the separation standards, the rate at which collisions will occur (for every 10,000,000 flight hours) in an ATC environment where there is no traffic surveillance. The model is concerned with extremely unlikely and rare events and, consequently, must deal with the extreme tails (several standard deviations away from the mean) of probability distributions for navigation errors. The NAT SPG, with the assistance of the Reich model, arrived at a consensus on a set of standards - after some six years of work and after several international meetings on the subject. An excellent account of this work has been written by R. Machol (see documents under Model B1.7). His paper provides a clear insight into the difficulties of working in the safety area. The difficulties are both technical (e.g., obtaining data for the extreme tails of distributions, accounting for blunders, etc.) and psychological (e.g. since it is not possible to ever achieve a probability of collision equal to zero, it is necessary to specify an "acceptable" probability of collision).

The Reich model and the work of NAT SPG has given rise to numerous derivative papers on this subject (for an extensive list see reports by Bradbury and by Keblawi listed in Section 8.6) and on other applications of the model (see reports by Hershkowitz and by Lloyd listed in Section 8.6).

A particularly interesting extension of the Reich model is reviewed here as Model B1.8. This represents an attempt to extend the original model to the case where a surveillance capability exists. This approach seems to be an ill-conceived one, since the presence of surveillance violates what is probably the most fundamental assumption in the Reich model, namely, that aircraft deviations from their ideal flight paths are statistically independent. With surveillance, it is possible to control aircraft as groups and, therefore, (at the very least) large navigation errors by neighboring aircraft might reasonably be expected



to be strongly correlated. A good review of the assumptions and logic of the Reich model and a discussion of possible extensions is given by Gilsinn (see Section 8.6).

Another type of ATC environment that lacks surveillance and control is the see-and-be-seen VFR environment that involves mostly general aviation aircraft. The only model that has seen some serious use for that environment is the so called "Gas Model."\* This model attempts to predict the likelihood of two aircraft coming into close proximity to each other and, by extension, the likelihood of mid-air collisions. As its name suggests, this model views aircraft as gas molecules moving randomly in a volume of space. It uses a classical analysis (borrowed from elementary physics) to estimate the rate at which aircraft come within close proximity of each other as a function of the density of aircraft per unit volume of airspace, the dimensions of the aircraft and of the protected airspace around each aircraft, and the relative speed of aircraft. The Gas Model was used by the U.S. Department of Transportation's ATC Advisory Committee as an aid in determining the specifications for the Intermittent Positive Control (IPC) system (see Section 8.6, Flanagan and Graham). The Gas Model has been criticized as unrealistic due to its assumption that aircraft move independently and in completely random directions in the region of interest. It would appear from this review that the Gas Model, nevertheless, still represents the state of the art when it comes to estimating conflict rates in an uncontrolled VFR environment.

The only alternative to the gas model that has apparently been developed since 1970 (for uncontrolled VFR flying) is Model B1.9 which examines conflict rates when VFR aircraft fly in a pattern (in this case a rectangular basic standard approach in the vicinity of airports which are not tower-equipped). The version of Model B1.9 which was reviewed is incomplete, but it represents a departure, conceptually, from the gas model. While the model's assumptions are more realistic than those of the gas model, the

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\*Reviewed as Model G-3 in Evaluation of Air Traffic Control Models and Simulations, Report No. DOT-TSC-FAA-71-7, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, June 1971.

difficulty of obtaining data that would help specify some of the model's inputs makes its application problematical.

The models discussed so far deal with operations of an ensemble of aircraft with specific traffic pattern scenarios (e.g. parallel straight tracks over the North Atlantic, random tracks for the gas model) in an uncontrolled environment. A model due to Bellantoni [Model Bl.5] examines the case of two aircraft attempting to fly prespecified flight paths of arbitrary shape. The model develops a mathematical expression for approximating the collision probability in this very general case, for any given set of separation standards. It is difficult, however, to use this mathematical expression in all but a few specific ATC contexts. The model's input data requirements are also severe.

A set of models developed at Collins Radio Company [Model Bl.4] employ a mathematical approach similar to Model Bl.5. There are, however, two important differences. First, the emphasis is shifted from estimating collision probabilities to specifying separation standards (and protected airspace volumes around aircraft) as a function of ATC system characteristics (e.g. navigation accuracy, surveillance update rate and accuracy, controller/pilot performance, etc.). Second, Model Bl.4 includes consideration of the presence of surveillance, and can therefore take into account the presence of an external control loop in a two-aircraft system. Model Bl.4 is also significant because it can be considered an antecedent of more recent work on various types of collision avoidance systems (see Koenke and Ratcliffe, Section 8.6), on collision avoidance maneuvers (see Palicio, Ratcliffe and Sorensen, Section 8.6) or on estimation of collision miss distances (see Ratcliffe and Sorensen, Section 8.6).

The next class of models in our review [Models Bl.1, Bl.2 and Bl.3] can, in a way, be interpreted as special cases of Models Bl.4 and Bl.5 for the near airport airspace. The emphasis in these models is on determining safe lateral separation standards between approaches to parallel runways [Models Bl.1 and Bl.2], or safe longitudinal separation standards on final approach [Model Bl.3]. The conceptual basis for the models is a simple one. A minimum separation standard is viewed as the sum total of the

effects of several safety-related contributing factors. One such factor, for instance, is separation imposed by physical requirements such as wake vortex avoidance. Another factor is the size of the airspace ("detection zone") needed to assure a high probability of the ground surveillance system detecting a blunder by one of the aircraft making an approach to parallel runways or a consecutive approach to a single runway. A third factor is the reaction time required by controllers, pilots and aircraft to decide on a response to a hazardous situation, and then to initiate and execute such responses. Once the contribution of each of these factors is determined, a separation standard to account for their combined effect can be specified. Unfortunately, and despite its conceptual simplicity, this approach suffers from problems similar to those we have already noted for other models: it imposes a severe input data requirement on the model's user due to the need for information on worst-case failure modes of human operators and equipment in the ATC system; and it calls for selection, by ATC planners of an acceptable level of risk in the ATC system, a difficult choice to make in the psychologically and politically sensitive area of aviation safety.

The last model reviewed here has a relatively modest objective: estimation of the number of potential conflicts that can be expected to arise per unit of time either at the intersection of two or more controlled, en route airways or along a straight-line segment of an air route [Model B1.6]. In the former case, we have a "crossing conflict" and in the latter an overtaking conflict. This model, due primarily to W. Dunlay, is a practical, simple and effective one. It can be considered as the controlled en route airspace's version of the gas model. Rather than allow aircraft to fly without restrictions (and in random directions), it constrains traffic flows to a specified network of air route intersections. Given a definition of what constitutes a "conflict," the Dunlay model (just like the gas model) concerns itself only with the expected number of conflicts and not with how severe



the conflicts are or how they will be resolved. Completing the analogy to the gas model, Model B1.6 also assumes that the instants at which aircraft appear at air route intersections or enter air route segments are random, i.e. may be described by a (homogeneous) Poisson process.

Model B1.6 has also been reviewed in Section 5 (see Model A5.3 in Part III) because it can also be used to estimate the capacity of air routes. Unfortunately, the model may become less relevant as the use of Area Navigation (RNAV) grows in the United States ATC system, thus increasingly deviating from the strict airway network structure that the model assumes.

## 8.2 CLASSIFICATION OF MODELS

The classification scheme shown in Table 8-1 indicates which part of the ATC system each of the models reviewed is concerned with, and includes a further breakdown as to the assumption of a surveillance capability. Some models appear in the Table twice. For instance, Model B1.3 can be used to assess both VFR and IFR longitudinal separation standards on final approach and, consequently, can be used whether or not a surveillance capability exists. Similarly, Model B1.4 is sufficiently general to be usable in both of these cases.

Irrespective of the merits of existing models (in terms of providing satisfactory capabilities for the area(s) that each covers) one noteworthy aspect of Table 8-1 is the complete lack of a terminal area safety model for a controlled environment. (The gas model's assumptions are entirely unrealistic for such an environment.) This absence is particularly distressing since this is probably the one aspect of the ATC system for which a safety model would be most useful. On the other hand, the reasons for the non-existence of such a model are rather obvious: the lack of a simple route structure in the terminal area; the complex paths that aircraft often fly there; the continuous interaction of pilot and controller; and the frequent (and conscious) minor violation of separation standards that takes place during the final sequencing and spacing process. All these combine to make the terminal area situation a particularly difficult one to represent realistically in a model and to analyze from the safety point of view.

Another possible classification scheme for the models reviewed here is by type of output produced. In this respect, we have:

- i) Models that yield collision probabilities or conflict rates: B1.5, B1.6, B1.7, B1.8, B1.9 and the Gas Model.
- ii) Models that yield a specification of separation standards or of adequate protected airspace around aircraft: B1.1, B1.2, B1.3, B1.4.

TABLE 8-1. CLASSIFICATION OF SAFETY-RELATED MODELS

ATC Area Where Model Mostly Applies	Surveillance Present	No Surveillance Present
Final Approach	B1.1, B1.2, B1.3	B1.3
Terminal Area		B1.9, Gas Model
En Route	B1.6	Gas Model
Oceanic	B1.8	B1.7
General	B1.4	B1.4, B1.5



A fine discussion of a possible way to categorize safety models conceptually is provided by Haines in the Winter 1977 issue of Navigation (see Section 8.6).

### 8.3 GENERAL OBSERVATIONS AND CONCLUSIONS

The basic question that we have not addressed is whether existing safety-related models offer an adequate set of tools for dealing with important questions that arise most often in this area. The capabilities of existing models are rather limited, and oriented toward very specific problems. For instance, we have a good understanding of the "physics" of problems involving just two aircraft flying in certain types of controlled or uncontrolled environments (e.g. the North Atlantic model and the general two-aircraft collision avoidance models B1.4 and B1.5). Similarly, the problem of setting separation standards for well-structured cases (e.g. lateral separation between parallel runways) is well understood conceptually. Unfortunately, however, the state of the art is such that we cannot deal with more general situations and cannot answer many of the most significant questions.

These deficiencies are well-illustrated by two recent studies concerned with evaluating the potential safety-related benefits that would result from implementation of the Upgraded Third Generation ATC System (see, Section 8.6 - Battelle and Simpson). The studies were required to focus on the safety-related effects of the ATC equipment and procedures associated with the Upgraded Third Generation System in terminal and en route areas and in all types of traffic environments. The lack of adequate models for quantifying these effects in this general and important case forced both studies to take the following approach: A survey of historical data on air traffic accidents was conducted and accidents were classified according to the phase of flight in which they occurred (e.g., landing, takeoff, transition area, en route) and according to probable cause. Each innovation associated with the Upgraded Third Generation System (new equipment or changed procedures) was then examined separately to see what effect, if any, it can be expected to have on each category of accident. At this point,

those conducting the studies made some arbitrary decisions based on their own best judgement. For example, it is assumed by Simpson et al. that "DABS/IPC aircraft vs. DABS/IPC aircraft midair collisions will be prevented if the collision occurred within DABS en route coverage (range 110 nmi, elevation angle  $>0.25$  deg) and/or DABS terminal coverage, because position and altitude of both aircraft will be known and at least one aircraft will be contactable by the automated collision avoidance function." In a similar way, and since the study is concerned with the 1975-2000 time period, Simpson et al. proceed to derive (by linear extrapolation) the number of accidents that would occur in the absence of an Upgraded Third system, during that time period (using forecasts of aviation activity provided by the FAA). The forecasts of accidents, and the fractions of accidents in each category, that could be prevented by the Upgraded Third system are finally combined to arrive at an estimate of the safety-related benefits of the System. While the whole procedure clearly raises many questions, its use is dictated by our current inability to analyze through models many safety-related problems.

Some additional observations with respect to safety-related models are:

a. Irrespective of the ATC environment, all safety models show that the rate of expected conflicts/collisions increases in proportion to the square of traffic density. Although some writers make a lot of this relationship, it is a purely dimensional one: it results from the fact that the number of possible aircraft pairs (i.e. of "potential" collisions) increases as the square of the number of aircraft present.

b. Almost all models reviewed are analytical in nature. Simulation has not yet been used extensively in the analysis of safety-related problems in ATC.

c. One of the most fundamental issues in safety analysis has yet to be resolved. This is the question of how to treat blunders. Are blunders the "extremely unlikely" events that are

represented by the extreme tails of the usual probability density functions for navigation errors or, are they events of a nature and frequency that cannot be captured by these probability density functions (and must, therefore, be treated individually as "worst-case" analyses)? It is interesting in this respect to note that Model B1.7 (the North Atlantic model) adopts the former position while Models B1.1 through B1.4 adopt the latter.



#### 8.4 MODELS REVIEWED AND SUPPORTING DOCUMENTS

##### Model B1.1

Kullstam, P.A., "Parallel Runway Spacing," Navigation, 19, No. 1, pp. 19-28 (Spring 1972). [B1; A1]

##### Model B1.2

Haines, A.L. Reduction of Parallel Runway Requirements, Report MTR-6841, The MITRE Corporation, McLean, VA, January 1975. [B1; A1]

##### Model B1.3

Haines, A.L., Concepts for Determination of Longitudinal Separation Standards on Final Approach, Report MTR-7047, The MITRE Corporation, McLean, VA, October 1975. [B1; A1]

Sinha, A.N. and A.L. Haines, Longitudinal Separation Standards on Final Approach for Future ATC Environments, Report MTR-6979, The MITRE Corporation, McLean, VA, October 1975. [B1; A1]

##### Model B1.4

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Holt, J.M. and G.R. Marner, "Separation Hazard Criteria," Appendix C-4 in Report of Air Traffic Control Advisory Committee, U.S. Department of Transportation, Washington, DC, December 1969. [B1]

Holt, J.M. and G.R. Marner, "Separation Theory in Air Traffic Control System Design," Proceedings of the IEEE, 58, No. 3 (March 1970). [B1]

Holt, J.M., "Safe Separation in Controlled Flight," Navigation, 21, No. 1, pp. 1-8 (Spring 1974). [B1]

#### Model B1.5

Bellantoni, J.F., "The Calculation of Aircraft Collision Probability," Transportation Science, Volume 7, No. 4, pp. 317-339, November 1973. [B1]

#### Model B1.6

Dunlay, W.J., Jr., R. Horonjeff and A. Kanafani, Models for Estimating the Number of Conflicts Perceived by Air Traffic Controllers, Special Report, University of California at Berkeley, Institute of Transportation and Traffic Engineering, Berkeley, CA, December 1973. [B1; A5, A6]

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Dunlay, W.J., Jr., and R. Horonjeff, "Applications of Human Factors Data to Estimating Air Traffic Control Conflicts," Transportation Research, 8, No. 3, pp. 205-217 (August 1974). [B1; A5, A6]

Schmidt, D.K., "On the Conflict Frequency at Air Route Intersections," Transportation Research, 11, No. 3, pp. 351-355 (August 1977). [B1; A5, A6]

#### Model B1.7

Hershkowitz, R.M., Collision Risk Model for NAT Region, Report DOT-TSC-FAA-71-6, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, May 1971. [B1]

Reich, P.G., "Analysis of Long-Range Air Traffic Systems: Separation Standards, Parts I, II, and III," Journal of the Institute of Navigation, 19, No. 1, 2, and 3 (January, April and July 1966). [B1]

Machol, R.E., "An Aircraft Collision Model," Management Science, 21, No. 10 (June 1975). [B1]

Model B1.8

Tyler, J.S., D.E. Stepner and J.A. Sorensen, "An ATC/Surveillance Modelling Approach for Specifying Lane Separation Standards," Paper No. 10 in Air Traffic Control Systems: AGARD Conference Proceedings, Report AGARD-CP-105, NATO Advisory Group for Aerospace Research and Development, Brussels, Belgium, June 1973. [B1]

Gagne, G.A. and R.M. Hershkowitz, Oceanic Surveillance and Navigation Analysis, FY72, Report FAA-RD-72-142, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, August 1972. [B1]

Model B1.9

Baxa, E.G., Jr., L.L. Scharf, W.H. Ruedger, J.A. Modi, S.L. Wheelock and C.M. Davis, Studies of Uncontrolled Air Traffic Patterns, Report NASA CR-141397, National Aeronautics and Space Administration, Washington, DC, April 1975. [B1]



## 8.5. ATTAINABILITY OF COMPUTER PROGRAMS

Model	Is Computer Program Required?	Program Listing Included in Reviewed Documents?	Program User's Guide Publicly Available?	Can Computer Program be Readily Written?	Individuals (if known) and Organization to Contact for More Information on the Model
B1.1	No	No	No	Yes	Per A. Kullstam Computer Sciences Corporation 6565 Arlington Blvd. Falls Church, VA 22046
B1.2	No	No	No	Yes	Andrew L. Haines The MITRE Corporation 1820 Dolley Madison Blvd. McLean, VA 22102
B1.3	No	No	No	Yes	Andrew L. Haines The MITRE Corporation 1820 Dolley Madison Blvd. McLean, VA 22102
B1.4	No	No	No	Yes	J.M. Holt McDonnell Douglas Electronics Company St. Louis, MO.
B1.5	Yes	No	No	Yes	John Bellantoni U.S. Dept. of Transportation/TSC 55 Broadway Cambridge, MA 02142
B1.6	No	No	No	Yes	William J. Dunlay Peat, Marwick, Mitchell and Co. San Mateo, Cal. P.O. Box 8007 San Francisco International Airport San Francisco, CA 94128
B1.7	Yes	No	No	Yes	P.G. Reich Royal Aircraft Establishment United Kingdom
B1.8	Yes	No	No	No	J.S. Tyler Systems Control Inc. 1801 Page Mill Rd. Palo Alto, CA 94304
B1.9	Yes	No	Some Documentation	No	E.G. Baxa, Jr. Research Triangle Institute Research Triangle Park, N.C. 27709

## 8.6 OTHER RELATED REPORTS

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Braff, R. and S. Mohleji, Analysis of Route Widths in the Domestic Airspace, Report M63-226, The MITRE Corporation, McLean, VA, November 1973. [B1; A5]

Brooker, P. and T. Ingham, Collision Risk in Air Traffic Systems: The Derivation of the Longitudinal/Vertical Overlap Factor  $P_{xz}$  for Parallel Tracks, Report CAA-P-77004, Civil Aviation Authority, London, United Kingdom, April 1977. [B1]

Busch, A.C., B. Colamosca, and J.R. VanderVeer, Collision Risk and Economic Benefit Analysis of Composite Separation for the Central East Pacific Track System, U.S. Dept. of Transportation, National Aviation Facilities Experimental Center, Atlantic City, NJ, June 1977. [B1]

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Dunlay, W.J., Jr. and R. Horonjeff, "Applications of Human Factors Data to Estimating Air Traffic Control Conflicts," Transportation Research, 8, No. 3, pp. 205-217 (August 1974). [B1; A5, A6]

Flanagan, P.D. and K.E. Willis, "Frequency of Airspace Conflicts in the Mixed Terminal Environment," Appendix C-1 in Report of Air Traffic Control Advisory Committee, U.S. Department of Transportation, Washington, DC, December 1969. [B1]

Gilsinn, J.F., Mathematical Approaches to Evaluating Aircraft Vertical Separation Standards, Report FAA-EM-76-12, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, May 1976. [B1]

Graham, W. and R. H. Orr, "Terminal Air Traffic Model with Near Midair Collision and Midair Collision Comparison," Appendix C-3 in Report of Air Traffic Control Advisory Committee, U.S. Dept. of Transportation, Washington, DC, December 1969. [B1]

Haines, A.L., Reduction of Parallel Runway Requirements, Report MTR-6282, The MITRE Corporation, McLean, VA, January 1973. [B1; A1]

Haines, A.L., A General Model for Separation Standard Assessment, Report MTR-6909, The MITRE Corporation, McLean, VA, May 1975. [B1; A1]

Haines, A.L., Aircraft Separation Standards, A Case Study, Report M77-79, The MITRE Corporation, McLean, VA, 1977. [B1; A1]

Haines, A.L., "Concerning the Logical Comparison of ATC Separation Standard Assessment Models," Navigation, 24, No. 4, pp. 345-351 (Winter 1977-1978). [B1]

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Koenke, E.J., A Theory of Aircraft Collision Avoidance System Design and Evaluation, Report DOT-TSC-OST-71-4, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, May 1971. [B1]

Lloyd, D.E., "Mathematical Studies on Separation Standards," Journal of the Institute of Navigation, 24, No. 4 (October 1971). [B1]



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Siddiquee, W., Computer-Aided Traffic/Airway/VOR(TAC) Network Methodologies, Volumes I and II, Report FAA-RD-72-118, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, August 1972. [A5; A6, B1]

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## 8.7 REPORTS NOT REVIEWED

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Kirkendall, N.J., Review of the Working Papers of Working Group C of the RGCSP on Lateral Separation Standards in European En Route Areas, Report MTR-6882, The MITRE Corporation, McLean, VA, August 1975. [B1; A5]

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Lloyd, D.E. and P.P. Scott, Application of Monte-Carlo Methods to Estimation of Collision Risk Associated with ATC Separation Standards, Report 73104, Royal Aircraft Establishment, United Kingdom, June 1973. [B1]



McIvor, D.E., Sensitivity of Intermittent Positive Control Conflict Rate and Processor Load Estimates to Protection Volume Parameters, Report MTR-6308, The MITRE Corporation, McLean, VA, 1973. [B1]

McIvor, D.E. and J.S. Matney, Analysis of Intermittent Positive Control Conflict Rates and Computer Processing, Report MTR-6175, The MITRE Corporation, McLean, VA, 1972. [B1]

Mundra, A.D., Air Traffic at an Uncontrolled Airport and Expected Alert Rates for Collision Detection Logics, Report FAA-EM-76-5, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, 1976. [B1]

Palmieri, S. et al., "An Air Traffic Simulation Model for the Area Around an Airport, Directed Particularly Toward the Study of Collision," in Collision Avoidance and Rendezvous Navigation: Proceedings of the International Congress, Hanover, West Germany, October 2-5, 1973, Volume 2, Duesseldorf: Deutsche Gessellschaft Fur Ortung und Navigation, 1974. [B1; A4]

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Stepner, D.E., Modeling of Aircraft Position Errors with Independent Surveillance, Report on file at U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, 1973. [B1; A5]

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## 9. NOISE-RELATED MODELS (CATEGORY C1)

The two models reviewed in this category (see Section 9.2) deal with noise levels generated by aircraft taking off or landing at airports. Attainability of computer programs for the models in this category is indicated in Section 9.3.

### 9.1 OVERVIEW OF MODELS

Model C1.1, the "Integrated Noise Model," computes community noise exposure levels in the area surrounding the airport for a given pattern of aircraft approaches and departures. This model has been selected as the "official" model by the FAA (in that it meets the requirements of FAA Order 1050.1B) to be used in Environmental Impact Statements, and it is being extensively documented at this time for the purpose of giving it the widest possible distribution. The Integrated Noise Model (INM) contains, at least in theory, the desirable features of other similar computer models developed by Mitre, Wiley Laboratories, and Bolt, Beranek and Newman. Reports related to these other models are listed in Section 9.4, but no detailed reviews were prepared since they have been superseded by the Integrated Noise Model.

Model C1.2 (ANOPP, Aircraft Noise Prediction Program), performs a different task. Given preliminary design information about a future aircraft and/or engine, it predicts the noise levels generated by a flyover trajectory. Thus, it can supply noise source information needed by the Integrated Noise Model, particularly when operations by new aircraft are projected.

Both models are in a state of continuing development. The INM needs to be tested further and validated so that an acceptable measure of confidence in its ability to predict community noise exposure levels can be established. Since there is a considerable variation in operational noise levels recorded by a microphone for any aircraft type, and the mean operational values may not agree

with certification data, noise data under operational conditions must be gathered over an extended period of time at an airport where a good noise monitoring system exists. These data will enhance statistical confidence in the mean operational values to be used by the INM.

The ANOPP program shows an excellent correlation between predicted and actual noise levels in early validation studies. Further validation tests are underway to compare model predictions with noise generated by wide body transport aircraft.

In general, the state of the art for airport noise-related models seems to be satisfactory. It is necessary, however, to continue the development and validation of the two computer models reviewed here, to develop some degree of confidence in the model results.

## 9.2 MODELS REVIEWED AND SUPPORTING DOCUMENTS

### Model C1.1

U.S. Dept. of Transportation, FAA Integrated Noise Model-Version 1, Basic User's Guide, Report FAA-EQ-78-01, Federal Aviation Administration, Office of Environmental Quality, Washington, DC, December 1977. [C1]

U.S. Dept. of Transportation, FAA Integrated Noise Model-Version 1, Computer Installation Instructions, Report FAA-EQ-78-03, Federal Aviation Administration, Office of Environmental Quality, Washington, DC, January 1978. [C1]

### Model C1.2

Raney, J.P., Noise Prediction Technology for CTOL Aircraft, NASA Conference Publication 2036, Part II, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, March 1978. [C1]



### 9.3 ATTAINABILITY OF COMPUTER PROGRAMS

Model	Is Computer Program Required?	Program Listing Included in Reviewed Documents?	Program User's Guide Publicly Available?	Can Computer Program Be Readily Written?	Individuals (if known) and Organization to Contact for More Information on the Model
Cl.1	Yes	Yes	Yes	No	Robert Hinckley U.S. Dept. of Transportation/TSC 55 Broadway Cambridge, MA 02142
Cl.2	Yes	No	No	No	John P. Raney NASA Langley Research Center Hampton, VA 23365

#### 9.4 OTHER RELATED REPORTS

Bartel, C., C. Coughlin, J. Moran, and L. Watkins, Airport Noise Reduction Forecast, Volumes I and II, Report on file at U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, October 1974. [C1]

Galloway, W.J., Community Noise Exposure Resulting from Aircraft Operations: Technical Review, Report AMRL-TR-73-106, Air Force Systems Command, Aerospace Medical Research Laboratory, Wright-Patterson AFB, OH, November 1974. [C1]

Hinckley, R.H. and J.E. Wesler, The Noise Exposure Model (Mod 4), Report DOT-TSC-OST-71-14, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, August 1971. [C1]

Horonjeff, R.D., R.R. Kandukari and N.H. Reddingius, Community Noise Exposure Resulting from Aircraft Operations: Computer Program Description, Report AMRL-TR-73-109, Air Force Systems Command, Aerospace Medical Research Laboratory, Wright-Patterson AFB, OH, November 1974. [C1]

Mansbach, P.A. and F.X. Maginnis, FAA Integrated Noise Model User's Guide, Report FAA-EQ-76-2, U.S. Dept. of Transportation, Federal Aviation Administration, Washington, DC, March 1976. [C1]

Reddingius, N.H., Community Noise Exposure Modeling with the Noisemap Computer Program, Bolt, Beranek and Newman, Inc., Los Angeles, CA, 1975 [C1]

Reddingius, N.H., Community Noise Exposure Resulting from Aircraft Operations: Noisemap Program Operator's Manual, Bolt, Beranek and Newman, Inc., Los Angeles, CA, 1976. [C1]

#### 9.5 REPORTS NOT REVIEWED

Munch, C.L., Prediction of V/STOL Noise for Application to Community Noise Exposure, United Aircraft Corporation, Sikorsky Aircraft Division, Stratford, CT, May 1973. [C1]

Patterson, H.P., R.P. Edmiston and W.K. Connor, Preliminary Evaluation of the Effect of a Dynamic Preferential Runway System Upon Community Noise Disturbance, Tracor, Inc., Dallas, TX, 1972. [C1]

Taub, J., T. Foreman and B. Brownfield, The Noise Exposure Model, MOD 5, Volumes I and II, U.S. Dept. of Transportation, Transportation Systems Center, Cambridge, MA, November 1971. [C1]



PART III  
DETAILED MODEL REVIEWS

## MODEL A1.1

1. Primary Model Category: Capacity-Oriented Runway Models
2. Report Used to Evaluate the Model:

Title: Models for Runway Capacity Analysis

Author: Richard M. Harris

Agency: The MITRE Corporation

Report #: MTR-4102, Revision 2

Date: December 1972

Other I.D.: Contract No. DOT-FA70WA-2448

3. Author's Abstract: This report examines a family of mathematical and simulation models for the calculation of single runway IFR capacity. With the basic statistical model one can calculate basic saturation capacity under arrival only and mixed arrival/departure operations. In addition, extensions have been made into the analysis of less-than-saturation demand by a simple queueing model and of speed-class sequencing as a Markov process. A statistical model is used to predict capacities for alternative runway configurations, levels of approach control system precision, and changes in aircraft separation standards. This analysis was performed in support of the Department of Transportation Air Traffic Control Advisory Committee and was used to compare alternative ways of increasing the IFR capacity of both single and parallel runways.

Reviewer's Note: This review is concerned only with the saturation capacity models presented in the above report. These are covered in Chapters 1, 2 and 3 of the report. While the queueing model in the Harris report is interesting, it has been superseded by more realistic models (see Section 2, Part II, on Delay-Oriented Runway Models) that have appeared since 1972.

### 4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: The model relates aircraft performance characteristics, aircraft safety separation standards, approach control delivery precision, aircraft

mix and runway operating strategy to the capacity of runways used for landings only, for takeoffs only, or for mixed operations.

4.3 Input Data Requirements: Aircraft mix; final approach velocity by aircraft type; runway occupancy time; aircraft safety separation standards; approach control delivery precision (expressed as a probability distribution of aircraft deviation from its expected position on final approach); acceptable probability (e.g., 0.01) of violating minimum separation standards; length of final approach; controller strategy for interleaving departures between successive arrivals when the runway is used for mixed operations.

4.4 Outputs Obtainable: Hourly capacity of a single runway when used for landings only, for takeoffs only, or for mixed operations.

5. Computer-Related Characteristics: The computer implementation of this model is not discussed in this report. However, since this is a rather simple analytical model, writing a program to produce numerical estimates based on the model is a straightforward task. Computational cost of model runs should be minimal.

6. Major Assumptions: The probability distribution of gate delivery times, final approach speeds, and runway occupancy times are normal (Gaussian); each aircraft type has its own constant final approach speed; the types of successive arriving aircraft are statistically independent; when operations on a runway are mixed, departures on the runway can be released in one of two ways: (i) when a sufficiently long time gap between minimally separated arrivals exists, or (ii) between each pair of successive arrivals when arrival spacing has been adjusted to allow the interleaving of one departure between each pair of arrivals.

7. Status of Model: No information is provided in this report. However, it is known that this model and its derivatives (see review of Model A1.2) has provided the basis for computer programs used in numerous FAA-sponsored projects to evaluate runway capacities under various sets of conditions.

8. Quality of Documentation: The presentation of the logic, assumptions and analysis of the models is well-organized and



lucid, and includes many illustrative examples.

9. Extent of Model Validation: No information is presented.

10. Modularity and Flexibility: The models presented can easily be combined with delay-oriented models of runway operations for a complete analysis of congestion problems at an airport.

11. Evaluation: This can be considered the "generic" model in this area in that it combines almost all of the best features of pre-1972 capacity models and provides the basis for subsequent more general models. Thus, the prospective user of capacity-oriented models would be well-advised to become thoroughly familiar with this model. (As noted above, studying Chapters 1, 2, and 3 of Harris' report will suffice for this purpose).

The major deficiencies of this capacity model are that: (i) it considers only single runway situations; (ii) some of its error and buffering analysis could be greatly simplified with negligible loss in the accuracy of the results; and (iii) it does not explicitly consider wide-body aircraft (except in Appendix E) and their effect on runway capacity due to the magnitude of the minimum separations required behind these aircraft.

All of these difficulties have been overcome by subsequent models (see reviews of Models A1.2 and A1.3) which, however, borrow heavily from this model and can be considered derivatives of it.

## MODEL A1.2

### 1. Primary Model Category: Capacity-Oriented Runway Models

### 2. Report Used to Evaluate the Model:

Title: Concepts for Estimating Capacity of Basic Runway Configurations

Authors: F. A. Amodeo, A. L. Haines, and A. N. Sinha

Agency: The MITRE Corporation

Report #: MTR-7115

Date: March 1977

Other I.D.: Contract Number DOT-FA70WA-2448

3. Authors' Abstract: One method of evaluating the impact of changes in the governing longitudinal separation standards on final approach is through the estimation of runway capacity. This paper presents concepts for such an estimation. The arrival stream is analyzed with respect to the applicable longitudinal separation standards, ATC system performance and the interactions with departures, if any, as governed by the appropriate ATC rules and procedures. Concepts are developed for arrival only, departure only, arrival/departure, dual-lane, and intersecting runway configurations. The revision updates the January 1976 version, primarily with respect to the detail of dealing with intersecting runway configurations.

### 4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates airport, ATC, and user related factors (see input data requirements below) to the capacity of a runway or of a combination of runways.

4.3 Input Data Requirements: Aircraft mix; approach and final velocity by aircraft type; location of localizer and glide slope intercepts; minimum separation requirements for arrival-arrival, departure-departure, and departure-arrival sequences; mean and variance of arrival runway occupancy time; departure runway

occupancy time; arrival-departure time separation; departure time to clear intersection; number of standard deviations of runway occupancy time and of metering and spacing buffer to be protected.

4.4 Outputs Obtainable: Throughput hourly capacity of a single, dual-lane, or intersecting runway configuration.

5. Computer-Related Characteristics: These are not discussed but the computer program needed to implement these models is rather simple to write. The authors of this report have written such a program, which is now extensively used at MITRE/Metrek.

6. Major Assumptions: Each aircraft type has its own constant approach and final velocities with speed changes occurring instantaneously; the types of successive aircraft are statistically independent; aircraft of all types are present at any time in the prescribed mix; mixed operations follow an alternating priority scheme with 50% arrivals and 50% departures in an hour; for mixed operations in VFR weather each departing aircraft is assumed to be of the same type as the landing aircraft immediately preceding it; for mixed operations in IFR weather, the same assumption is made and then a correction factor is included; separation requirements are adhered to with a small probability of violation; only CTOL aircraft are considered.

7. Status of Model: The computer program associated with this model has been used extensively in connection with several FAA-sponsored projects. Although no information is given on this topic, computational costs should be minimal, due to the simplicity of the model.

8. Quality of Documentation: The logic of the model is clearly, although rather briefly presented (complete familiarity with the model of Harris, Al.1, is assumed). However, the reasons for some of the basic assumptions are not stated. In addition, important omissions occur in the description of the model's application to the cases of a single runway used for both landings and takeoffs, dual lane runways, and intersecting runways. In none of these cases is it explained how the metering and spacing buffers are to be included. A reader is thus unlikely to be able to reproduce



the capacities given in the illustrative example for these cases, relying solely on the information provided in the reference document. The single example, containing only inputs and outputs without intermediate results, makes it difficult for the reader to understand the inner workings of the model or its sensitivities.

9. Extent of Model Validation: No information is presented on model validation.

10. Modularity and Flexibility: The model can easily be combined with delay-oriented models of runway operations for a complete analysis of congestion problems at an airport.

11. Evaluation: This model examines important extensions to Model A1.1 to account for the presence of wide-body aircraft and for two-runway (dependent) airport configurations. The model should lead to reliable estimates of capacity. However, under mixed operations, it considers only the case of perfectly controlled sequences of arrivals alternating with departures (50% landings, 50% takeoffs; arrival followed by departure followed by arrival, etc.). Examination of other than 50-50 mixes is also desirable as well as consideration of the probability that more than one departure can be inserted between two successive landings (see Model A1.3).

Another questionable assumption is that, under mixed operations, each landing aircraft is followed by a departing aircraft of the same type. This is unrealistic and does little to simplify the computations, especially when the model is programmed on a computer. Also, the correction factor applied for mixed operations under IFR conditions is not justified in the report.

Use of this model is recommended because of its simplicity and its obvious ability to produce reliable estimates of capacity for most situations currently encountered at airports. However, as noted in Item 8 above, the user may have difficulty in interpreting some aspects of the model documentation.

### MODEL A1.3

1. Primary Model Category: Capacity-Oriented Runway Models

2. Reports Used to Evaluate the Model

i) Title: Developments in Airport Capacity Analysis

Author: Stephen L. M. Hockaday and Adib K. Kanafani

Agency: Peat, Marwick, Mitchell and Co. and University of California, Berkeley, California

Report #: Transportation Research, Vol. 8, No. 3, pp. 171-180

Date: August 1974

ii) Title: Procedures for Determination of Airport Capacity, Vol. 1 and II

Authors: Anonymous

Agency: Douglas Aircraft Co., McDonnell Douglas Corporation, Long Beach, CA

Report #: FAA-RD-73-11

Date: April 1973

Other I.D.: NTIS No. AD-763560; Contract No. DOT-FA72WA-2897

iii) Title: Model User's Manual for Airfield Capacity and Delay Models, Book 1

Author: Carl T. Ball

Agency: Federal Aviation Administration, U.S. Department of Transportation

Report #: FAA-RD-76-128

Date: November 1976

3. Authors' Abstract: Runway capacity is defined as the maximum number of aircraft operations that can be handled during a specific period of time, under given operating conditions. The most important determinants of capacity are the aircraft mix, the length of the common approach path, and the operating strategy.

Aircraft are postulated to deviate from intended paths while

approaching a runway to land. These deviations are assumed to be normally distributed random variables with zero means. In order to maintain the probability of violations of aircraft separation rules, controllers are assumed to introduce buffers between aircraft in order to absorb the randomness in their separations. A capacity model is constructed with these postulates. The model yields runway capacity for various operating strategies and permits the choice of the optimal strategy for any given and intended arrival-departure mix. The application of the model is demonstrated with data from New York's La Guardia Airport.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: This model is sensitive to air traffic characteristics, to separation standards and to rules and procedures in the terminal area.

4.3 Input Data Requirements: Aircraft mix; minimum longitudinal separation requirement on final approach; aircraft approach speeds; length of final approach path; mean and standard deviation of arrival and departure runway occupancy times; minimum separation between departures, between departures-followed-by-arrivals, and arrivals-followed-by-departures; standard deviations of the time needed to begin a takeoff roll and aircraft positions errors on final approach.

4.4 Outputs Obtainable: Hourly capacity of a runway system as a function of the percent of arrivals and departures during the hour in question.

5. Computer-Related Characteristics: The analytical model itself is quite complicated and, therefore, a computer program implementing the model might be expected to be quite sophisticated, as well. A computer program for this model has been written in FORTRAN and is available (see item 7 below). No information on typical running times is given.

6. Major Assumptions: The model assumes that arrivals are given priority over departures for the use of the runway (i.e.,



a landing will not be delayed on account of a departure); separation standards will be violated with small but known probability of violation; several types of spacing errors (at the runway threshold, at the gate to the final approach, etc.) are present and their standard deviations are known; a maximum of three departures may be able to takeoff between any two successive arrivals; all probability distributions for the variables in the model are normal; aircraft are served on a first-come, first-serve basis, i.e., controllers do not attempt to modify aircraft sequences.

7. Status of Model: This model is the one used to obtain the airport capacity estimates presented in the recently-issued Handbook of Airport Capacities and Delays (see Douglas Aircraft Co., Techniques for, etc. in Section 1.8 of Part II). As such the model has been extensively used. A computer program implementing the model is available to users through the FAA at a nominal cost.

8. Quality of Documentation: The documentation of the model is confusing and typographical errors are frequent, especially in the first of the references cited, and detract from comprehensibility. Several symbols are used without being defined. Also a documentation gap exists between the early and the final versions of the model (see references ii and iii cited above). No listing of the computer program is provided in the references reviewed.

9. Extent of Model Validation: The model has been validated against data from La Guardia Airport in New York, Chicago O'Hare Airport, Dallas Love Field and Orange County Airport. It is impossible to judge the quality and extent of the validation from the limited information provided in the reports used to evaluate this model.

10. Modularity and Flexibility: This model can be combined with a delay-oriented model of runway operations to produce delay estimates.

11. Evaluation: The primary contribution of this model is to extend the model of Harris (See A1.1) to the case in which the mix of operations (relative percentage of landings and takeoffs) can

be allocated among runways to maximize capacity. It also examines explicitly more runway configurations than Model A1.2. Unfortunately the description of the procedure used is quite sketchy and some steps (e.g., equation (28) in the first reference cited) are of questionable validity.

The interested reader is encouraged to review the model of Harris (see Model A1.1) before attempting to understand the present model. Use of this model is recommended only after the user has gained a full understanding of all its assumptions and limitations.

#### MODEL A1.4

1. Primary Model Category: Capacity-Oriented Runway Models

2. Reports Used to Evaluate the Model:

i) Title: Effect of Multiple Path Approach Procedures on Runway Landing Capacity

Author: Vojin Tosic and Robert Horonjeff

Agency: Institute of Transportation Studies, University of California, Berkeley, California

Report #: Transportation Research, Vol. 10, No. 5., pp. 319-329

Date: October 1976

Other I.D.: NASA grant NSG 2046

ii) Title: Models for Estimating Landing Capacity with Microwave Landing Systems (MLS)

Authors: V. Tosic and R. Horonjeff

Agency: Institute of Transportation Studies, University of California, Berkeley, California

Report #: Special Report No. 123

Date: 1975

Other I.D.: NASA Grant NSG 2046

3. Author's Abstract: When using the Instrument Landing System (ILS), all aircraft must follow a straight line approach path before landing. The Microwave Landing System (MLS) will allow use of differing curved approach paths.

The object of this research is to find out whether the introduction of MLS and consequently multiple approach paths can bring an increase in runway landing capacity.

A model is developed which is capable of computing the expected ultimate landing runway capacity, under ILS and MLS conditions, when aircraft population characteristics and Air Traffic Control separation rules are given. This model can be applied in situations when only a horizontal separation between aircraft approaching a runway is allowed, as well as when vertical and horizontal separations are possible.



Results suggest that an increase in runway landing capacity, caused by introducing the MLS-described multiple approach paths, is to be expected only when an aircraft population consists of aircraft with significantly differing approach velocities and particularly in situations when a vertical separation can be applied.

4. Model Description:

4.1 Model Type: Analytical; deterministic

4.2 Factors of National Airspace System Related to Model: The model in this report is sensitive to separation standards and to rules and procedures in the terminal area with microwave landing system (MLS) technology. It is also sensitive to air traffic characteristics.

4.3 Input Data Requirements: Aircraft mix; angle of approach for each aircraft type on final approach when MLS is available; minimum horizontal or vertical separation requirements on final approach; final approach speed by aircraft type.

4.4 Outputs Obtainable: Hourly capacity of a runway used only for landings.

5. Computer-Related Characteristics: It is simple to write a computer program that implements the two proposed analytical models. The authors of the report have written such a program, a listing of which appears in the second document under item 2. The program is in FORTRAN.

6. Major Assumptions: This model assumes that:

- i) the MLS and ILS approaches are error-free;
- ii) runway occupancy times are insignificant by comparison to the time required to cover the minimum horizontal separation distance in the air and can, therefore, be ignored;
- iii) each aircraft type has its own constant approach speed;
- iv) the types of successive arriving aircraft are statistically independent.

7. Status of Model: No information is provided on whether this model has been used in connection with a specific project.
8. Quality of Documentation: With minor exceptions (two mathematical functions, for instance, are mentioned but not made explicit), the analytical results are well documented. A computer program listing appears in the second document under item 2.
9. Extent of Model Validation: No information is presented.
10. Modularity and Flexibility: The models presented can easily be used with more general analytical models or simulations of airport and terminal area operations.
11. Evaluation: The analytical models presented in this report provide good approximations of landing capacity with the MLS system. However, two of its assumptions (see item 6 above), are subject to question. Runway occupancy time can sometimes be a constraining factor on runway capacity and should not, therefore, be always ignored. In addition, the model's implicit assumption that all aircraft can be delivered at their designated point of interception of the approach path at exactly the desired time is optimistic and can lead to some over-estimation of runway capacity. It is quite simple to extend the model so as to make allowances for errors in delivery time and for runway occupancy times. The model should also be extended to mixed runway operations.

This report provides a good starting point for future research in this area and its use is recommended.

## MODEL A1.5

1. Primary Model Category: Capacity-Oriented Runway Models

2. Report Used to Evaluate the Model:

Title: An Extension of the Throughput Runway Capacity  
Methodology to Include Multiple Glide Path Lengths and  
Angles

Author: A. P. Smith

Agency: The MITRE Corporation

Report #: MTR-6338, Vol. V

Date: May 1973

Other I.D.: Contract No. DOT-FA69NS-162

3. Author's Abstract: This paper extends the single runway IFR capacity methodology developed in MTR-4102 (see Model A1.1) to include multiple glide path lengths and angles. Particular emphasis was placed on examples which are representative of short-haul operations. Analysis was performed to indicate the sensitivity of the model to the glide path parameters, approach control system precision, separation standards, and approach speed mixes. A combination of altitude and longitudinal separations on the glide path is considered as a means of increasing capacity.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: This model is sensitive to air traffic characteristics, to separation standards, and to rules and procedures in the terminal area using the microwave landing system technology.

4.3 Input Data Requirements: Aircraft mix; angle and length of final approach for each aircraft type; final approach speed of aircraft; minimum horizontal and vertical separation requirements; and standard deviations of errors in approach speed, time of arrival at the gate, and runway occupancy time.

4.4 Outputs Obtainable: Capacity of a single runway or dual-lane



runways for mixed operations (both landings and takeoffs).

5. Computer-Related Characteristics: Not discussed in this report. It would be rather simple to write a computer program that implements the described models. Such a program has apparently been written by the author, as indicated by the numerical results presented in the report.

6. Major Assumptions:

- i) Errors in the gate delivery time, final approach speed, and runway occupancy time are assumed to have a normal (Gaussian) probability distribution;
- ii) once the approach speed for any particular aircraft has been determined that speed remains constant during final approach;
- iii) the types of successive arriving aircraft are independent;
- iv) departures are released 1) when a sufficiently long time gap between minimally separated arrivals exists or 2) between each pair of successive arrivals when arrival spacing has been adjusted to allow the interleaving of landings and takeoffs;
- v) slower aircraft follow a steeper final approach path with a final approach gate closer to the runway threshold than the gate of the final approach for faster aircraft;
- vi) in the dual lane runway configuration, arrivals and departures take place on separate runways.

7. Status of Model: No information is provided as to whether this model has been used, or if any more recent modifications of the model have been made.

8. Quality of Documentation: The analytical model (assumptions, equations, etc.) is presented clearly and correctly. There is no documentation of a computer program.

9. Extent of Model Validation: No information is presented.

10. Modularity and Flexibility: This model can easily be combined

with a delay-oriented runway model to produce delay estimates for airports equipped with microwave landing systems.

11. Evaluation: This report extends the work of Harris (see Model A1.1) and familiarity with that model is assumed by the developer of the present model. The extension is to the situation of multiple glide path lengths and angles, a situation which may become predominant in the future with the advent of the Microwave Landing System. Thus, this model covers the same area as the work of Tasic (Model A1.4) but extends that model to the cases of mixed operations and of dual-lane runways. Both models should provide good approximate estimates of runway capacity with MLS deployed. The two models are basically very similar and their results should be almost identical. A worthwhile extension of both models would be to explore capacity changes as the percentage of landings vs. the percentage of takeoffs changes.

## MODEL A1.6

1. Primary Model Category: Capacity-Oriented Runway Models

2. Report Used to Evaluate the Model:

Title: A Dynamic Programming Model for Optimal Location of Runway Exits

Author: Hans G. Daellenbach

Agency: Department of Economics, University of Canterbury, Christchurch, New Zealand

Report #: Transportation Research, Volume 8, No. 3, pp. 225-232

Date: August 1974

3. Author's Abstract: The time required by a landing aircraft to clear the runway depends, among other things on the type and location of runway exits available. For any given runway arrival pattern, in particular the aircraft separation times, the distribution of runway occupancy times determines the probability that the aircraft next in line for landing will be waved off. Horonjeff et al., (1959) prove that in the limit the expected runway acceptance rate is a function of the wave-off probability, and then, by the use of calculus, determine optimal locations for up to three high-speed runway exits so as to maximize the expected runway acceptance rate for a bivariate normal distribution of runway deceleration distances and times. This note shows how this optimization can more efficiently be done by the use of dynamic programming for any arbitrary joint probability distribution of deceleration distances and times and any number of exits. The paper also explores several extensions to the basic model.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates aircraft characteristics (on the runway) and runway exit locations to the acceptance rate of runways. This rate, in turn, can be used to estimate runway capacity.



4.3 Input Data Requirements: Aircraft mix; mean and standard deviation of deceleration time and distance for landing aircraft; correlation coefficient between deceleration time and distance; times needed to clear high-speed and right-angle runway exits; deceleration distance for a right-angle exit; number of high-speed exits; runway length.

4.4 Outputs Obtainable: High-speed runway exit locations such that the average runway acceptance rate is maximized or the expected total operating costs for aircraft using the runway are minimized.

5. Computer-Related Characteristics: Some discussion of computerization times is included in the paper but the computer program used to implement the model is not presented or described. It does not appear that it would be easy to write such a program.

6. Major Assumptions: Aircraft are categorized in types by landing and deceleration characteristics; all aircraft must decelerate to a specified speed depending on the type of exit, before leaving the runway; the distance and time for this deceleration are correlated random variables; if an aircraft occupies the runway for more than the inter-arrival separation time allowed, the next aircraft is waved off; a continuous stream of aircraft is always available in the prescribed mix; the probability of two consecutive wave-offs is negligible.

7. Status of the Model: No indication is given as to whether this model has ever been used in a practical application.

8. Quality of Documentation: The analytical results are well documented and the model is explained carefully with well-chosen examples. The computer program used is not discussed.

9. Extent of Model Validation: No information is presented.

10. Modularity and Flexibility: This model can be included in more general models of airport operations to help determine runway occupancy times.

11. Evaluation: The primary application of the model is in locat-

ing exits to maximize runway capacity. It is well-known, however, that as long as the locations of exits are reasonable, the runway capacity is very insensitive to the exact placement of these exits. This is due to the fact that separations in the air between successive landing aircraft imply time gaps between successive landings which are considerably longer than runway occupancy times. This is also evident from Daellenbach's model which indicates that acceptance rates (based on runway occupancy times alone) of up to approximately 95 aircraft per hour can be achieved with any reasonable set of exit locations. This rate, of course, is much higher than the rate at which the final approach can "feed" aircraft to the runway.

It should also be mentioned that taxiing costs vary negligibly as exit locations move (as long, again, as exits are reasonably placed).

In conclusion, although this model leads to a mathematically elegant and interesting analysis, the time and expense of using it seem unnecessary.

### MODEL A1.7

1. Primary Model Category: Capacity-Oriented Runway Models

2. Report Used to Evaluate the Model:

Title: Extension of a Capacity Concept to Dual-Use Runways  
and Multi-Runway Configurations

Author: W. A. Horn

Agency: National Bureau of Standards

Report #: FAA-RD-71-19

Date: December 1971

Other I.D.: Contract No. DOT-FA69WAI-166

3. Author's Abstract: This document is based on a previous investigation which yielded a "maximum throughput rate" concept for the capacity of a facility serving a single stream of customers of various types, in particular a runway serving a stream of landing aircraft. The present study develops four extensions of this concept, of progressively broader scope, to facilitate serving several customer-streams. An explicit capacity formula is derived for each extension. The second extension is applied to a runway serving both landings and takeoffs, while the final extension provides a theoretical basis for evaluating the capacity of complexes of runways at airports. An appendix gives several illustrations of how such results can be used to analyze the enhancement of capacity by appropriate settings of operational parameters.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of the National Airspace System Related to the Model: Parameters related to the ATC system, the airport and the airport users (aircraft mix, separation standards, percentage and sequencing of landings and takeoffs, accuracy of navigation and spacings) are used to compute the capacity of a single runway or of simple combinations of runways.

4.3 Input Data Requirements: Final approach and lift-off speeds of all aircraft types; runway occupancy times; length of final



approach; minimum horizontal separation requirements; error "buffers" allowed by controllers between successive operations.

4.4 Outputs Obtainable: Expressions are given for the capacity of runways used for mixed operations and for the capacity of simple multi-runway configurations. It is also shown how to maximize the number of operations on the runway(s) by sequencing of the various classes of aircraft using the runway(s).

5. Computer-Related Characteristics: Not discussed in the report reviewed. It is not clear that a computer program for the proposed models has been written. Moreover writing such a program does not appear to be an easy task.

6. Major Assumptions: Each aircraft type has its own constant approach speed; service is first-come, first-serve for identical aircraft but some types of aircraft may enjoy priority over other types; there is continuous demand for runway use; the controller is free to sequence operations and aircraft types in any manner deemed appropriate.

7. Status of Model: No information is provided on whether this model has been used in connection with any particular project.

8. Quality of Documentation: The mathematical analysis leading to the main results from this model is rigorous and correct. However, the report would have benefited greatly from inclusion of numerical examples. As mentioned above, no discussion of any computer implementation issues is contained in this report.

9. Extent of Model Validation: No information is presented.

10. Modularity and Flexibility: The model is, by its nature, a self-contained one, being concerned with the maximization of the capacity of a runway or of a system of runways under mixed operations (landings and takeoffs). Because the mathematical analysis depends critically on all the assumptions made in the model, it would be quite difficult to modify it without retracing the analysis practically from scratch.

11. Evaluation: The author's desire to be mathematically rigorous

leads to a practically intractable mathematical analysis. The expressions derived for the capacity of a runway (and of systems of runways) are of little use because of their complexity. The attempt to show how to maximize the capacity of the runway(s) is also unsuccessful because it assumes that parameters, which in practice are predetermined (e.g., mix of traffic, sequences of aircraft), can be controlled by the air traffic controller.

### MODEL A2.1

1. Primary Model Category: Delay-Oriented Runway Models

2. Reports Used to Evaluate the Model:

- i) Title: Air-Terminal Queues under Time-Dependent Conditions  
Author: Bernard O. Koopman  
Agency: Arthur D. Little, Inc., Cambridge, MA  
Report #: Operations Research, Vol. 20, No. 6, pp. 1089-1114  
Date: November-December 1972  
Other I.D.: None
- ii) Title: Analytical Tools for the Study of Airport Congestion  
Author: Bernard O. Koopman  
Agency: Arthur D. Little, Inc., Cambridge, MA  
Report #: --  
Date: 1971  
Other I.D.: NTIS No. AD-730789

3. Author's Abstract: The queues formed by aircraft in stacks awaiting landing clearance have usually been treated either by machine simulation, or analytically as stochastic processes with time-independent transition probabilities (possessing stationary solutions). In contrast to such methods, the present paper regards the queue-developing process in question as strongly time-dependent, often with a diurnal (24-hour) periodicity. The formulation and treatment are entirely analytic and make use of machines only to solve the equations for the probabilities, by economical deterministic steps, using the coefficients as given in tabular form. Time-varying Poisson arrivals are assumed, and also an upper limit to queue length. Two laws of servicing are used: Poisson and fixed service time; these extremes are found to lead to numerically close results in the realistic case. This situation contrasts with the much cruder approximation for deterministic flow models. The stochastic equations belong to well studied types of differential or difference equations. When the coefficients have a 24-hour period, so does just one solution, all others approaching it. Actual airport statistics are made the basis of certain revealing computa-



tions. A perturbation method for treating multiple queues is outlined. The concrete results are exhibited as graphs.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates runway capacity and hourly demand to airport-specific delay measures.

4.3 Input Data Requirements: Hourly average demand and capacity levels; maximum number of aircraft that can be accepted in the takeoff and the landing queues.

4.4 Outputs Obtainable: Probabilities,  $P_n(t)$ , that  $n$  aircraft will be waiting to land or to take off at time  $t$  (for  $n = 0, 1, 2, \dots$ ) and related quantities (such as the expected number in the landing or takeoff queue) as a function of time.

5. Computer-Related Characteristics: A fourth-order Runge-Kutta computer subroutine is used to obtain an iterative solution to the model which does not distinguish between landings and takeoffs (single queue model). The program is not described in detail since computational efficiency was not an objective of the study. No program was written for the two-queue (separate landings and takeoffs) model.

6. Major Assumptions: It is assumed that aircraft arrive at the terminal area or at the runways used for takeoffs at random instants, i.e., according to a time-dependent Poisson process. Access to the runways is provided on a first-come, first-served basis. Two models are explored: one assumes the time a runway is occupied by an aircraft is a constant; the other assumes this time is a random variable with a negative exponential probability density function. An airport is represented as a single runway, with airport capacity equal to the capacity of the runway. A maximum queue capacity is specified. Any aircraft that find this queue full upon arrival at the terminal area, are assumed to be diverted to "other" airports.

7. Status of Model: The computer program was written only for

illustrative purposes. This particular model has not been used since the time when it was first developed.

8. Quality of Documentation: The theoretical analysis is presented clearly and in precise mathematical language. The associated computer program is not described.

9. Extent of Model Validation: No attempt to validate the model has been made.

10. Modularity and Flexibility: This model is strictly a delay-estimation model. It must, therefore, be used with a capacity-determining model. The present model is entirely modular and can be easily included in a more extensive package of programs.

11. Evaluation: From the theoretical point of view, the report that describes this model is important in that it is the first major study of a time-dependent queueing model of a single runway. It contains two theoretically significant results: a proof that, given periodic demand and capacity inputs, a queue will exhibit periodic behavior; and a claim that airport delay characteristics are quite insensitive to the form of the probability density function for the time needed for a runway operation. Close examination of the graphs from which Koopman draws the latter conclusion, raises doubts as to whether his study provides sufficient evidence for such a claim.

The theoretical section on the two-queue model (landing queue and takeoff queue) contains a critical mistake and should be ignored by the reader. The mistake, roughly, is that it is not recognized that the equations for the behavior of the two queues also depend critically on the operating strategy used by the air traffic controller (i.e., on the sequencing of landings and takeoffs).

From the computational and applications point of view this model is obsolete (see derivative model by Hengsbach and Odoni A2.2). Koopman's paper, however, should be read because it provides the theoretical foundations for later, more advanced computer models.

## MODEL A2.2

1. Primary Model Category: Delay-Oriented Runway Models

2. Report Used to Evaluate the Model:

Title: Time-Dependent Estimates of Delays and Delay Costs at Major Airports

Author: Gerd Hengsbach and Amedeo R. Odoni

Agency: Flight Transportation Laboratory, MIT

Report #: R75-4

Date: January 1975

Other I.D.: None

3. Author's Abstract: Two queueing models appropriate for estimating time-dependent delays and delay costs at major airports are reviewed. The models use the demand and capacity profiles at any given airport as well as the number of runways there to compute bounds on queueing statistics. The bounds are obtained through the iterative solution of systems of equations describing the two models. This computational procedure is highly efficient and inexpensive. The assumptions and limitations of the model are discussed.

Common characteristics and properties of delay profiles at major airports are illustrated through a detailed example. Potential applications to the exploration of the effect of air traffic control innovations on congestion and to the estimation of marginal delay costs are also described.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates runway capacity and hourly demand to airport-specific delay measures.

4.3 Input Data Requirements: Hourly average demand and capacity levels; the number of runways at the airport; and the maximum number of aircraft that can be accepted in the takeoff and the landing queues.



4.4 Outputs Obtainable: Probabilities,  $P_n(t)$ , that  $n$  aircraft will be waiting to land or to takeoff at time  $t$  (for  $n = 0, 1, 2, \dots$ ) and related quantities, such as the expected waiting time for an aircraft as a function of time and the expected number of aircraft in the landing or takeoff queue as a function of time.

5. Computer-Related Characteristics: The computer program is written in FORTRAN H; typical costs are \$4 for analysis of a 24-hour period at a major airport (IBM 370/168 computer); the effort required to prepare inputs for the run is minimal.

6. Major Assumptions: It is assumed that aircraft arrive at the terminal area or at the runways used for takeoffs at random instants, i.e., according to a time-dependent Poisson process. Access to the runways is provided on a first-come, first-served basis. Two models are explored: one for which the probability density function for the duration of service times (i.e., for the time during which the runway is occupied by an aircraft) is a deterministic quantity and another for which this probability density function is a negative exponential random variable. Runways are assumed to operate independently. If that is not the case, the user of the model has to make adjustments to the capacity of the airport when providing the inputs to the model.

7. Status of Model: The model is being expanded at this time to include separate consideration of landings and takeoffs for various operations sequencing strategies other than first-come, first-served. More efficient computation techniques are also being included. The model has been used to produce a Handbook of Airport Delays (see report by Odoni and Kivestu in Section 2.9 of Part II) and to obtain delay estimates at Schiphol International Airport (Amsterdam, Holland), Arlanda International Airport (Stockholm, Sweden), Athens International Airport and several airports in the United States.

8. Quality of Documentation: The model's logic, assumptions and theoretical background are clearly and explicitly documented. Documentation of the computer program and/or a user's guide is not available.

9. Extent of Model Validation: No information is provided on any attempt to validate the model against field data.

10. Modularity and Flexibility: This model is strictly a delay-estimation model. It must, therefore, be used with a capacity-determining model.

11. Evaluation: This model extends the work of Koopman (see model A2.1) to the case of multiple runways. This extension is useful; however, because of the assumption that the runways are independent it must be used with care. For example, if an airport consists of two dependent runways and a third, independent runway, the capacities of these two distinct sets of runways will likely be unequal and appropriate adjustments must be made for the inputs to the model. Because of its very low cost of use and because of the fact that it is analytical (and, therefore, does not have to deal with questions of statistical convergence), the model can be very useful for obtaining good approximate estimates of average delays and other delay-related statistics at major airports. On the other hand, this model cannot provide more detailed information such as, for instance, what is the expected delay to a specific aircraft which is landing or taking off. In this respect, an important weakness of the model is that it does not distinguish between landings and takeoffs in those cases where a runway is being used for both types of operations.

This model has already been used in several projects (see item 7 above). The report that describes the model is well-written and provides a good starting point for further research in this area.

### MODEL A2.3

1. Primary Model Category: Delay-Oriented Runway Models

2. Reports Used to Evaluate the Model:

i) Title: Airport Demand/Capacity Analysis Methods

Author: Anonymous

Agency: Battelle Columbus Laboratories

Report #: Draft Report

Date: September 1974

ii) Title: Study for the Conversion of Short-Haul Airports;  
Interim Technical Report

Authors: J. W. Chadwick, V. J. Drago and D. G. Ullman

Agency: Battelle Columbus Laboratories

Report #: DOT-TSC-636

Date: March 1974

iii) Title: Prototype Cost/Benefit Results and Methodology for  
UG3RD System Capacity and Safety

Authors: Anonymous

Agency: Battelle Columbus Laboratories

Report #: Draft Final Technical Report

Date: June 1975

3. Reviewer's Summary: A model for performing a time-dependent analysis of delays at airports with an arbitrary number of runways is presented. It is assumed that demand for runway use can be described by a time-dependent Poisson process. The probability density function for the duration of service times is assumed to be a negative exponential. The airport capacity is assumed to be constant. Aircraft are served on a first-come, first-served basis.

The model consists of a system of first-order differential equations which are solved numerically with the aid of the computer. The model is almost identical to one of the two models incorporated in Model A2.2, with the exception that Model A2.2 allows the runway capacity to be a time-varying quantity.

4. Model Description:



- 4.1 Model Type: Analytical; probabilistic
- 4.2 Factors of National Airspace System Related to the Model: Relates runway capacity and hourly demand to airport-specific delay measures.
- 4.3 Input Data Requirements: Airport capacity and hourly average demand levels; the number of runways at the airport; and the maximum number of aircraft that can be accepted in the takeoff and landing queues.
- 4.4 Outputs Obtainable: Probabilities,  $P_n(t)$ , that  $n$  aircraft will be waiting to land or to takeoff at time  $t$  (for  $n = 0, 1, 2, \dots$ ) and related quantities, such as the expected waiting time for an aircraft as a function of time, and the expected number of aircraft in the landing or takeoff queue as a function of time.
5. Computer-Related Characteristics: A computer program has been written and sample outputs are shown. The program itself is not discussed in the documents reviewed nor are such items as typical running times, computer costs, etc.
6. Major Assumptions: It is assumed that aircraft arrive at the terminal area or at the runways used for takeoffs at random instants, i.e., according to a time-dependent Poisson process. Access to the runways is provided on a first-come, first-served basis. The probability density function for the duration of service times is a negative exponential with a constant average value. Runways are assumed to operate independently. If that is not the case, the user of the model has to make adjustments to the capacity of the airport when providing the inputs to the model.
7. Status of Model: The model has been utilized in connection with a study of the conversion of La Guardia Airport for exclusively short-haul use. It has also been applied to similar studies of Midway and Burbank Airports.
8. Quality of Documentation: The model's theoretical background is clearly and explicitly documented. The model's assumptions and computer-related characteristics are not explicitly discussed in the references reviewed.

9. Extent of Model Validation: No information is provided on any attempt to validate the model against field data.

10. Modularity and Flexibility: This model is strictly a delay-estimation model. It must, therefore, be used with a capacity-determining model. It is simple to do this.

11. Evaluation: This model is clearly superseded by Model A2.2, since it incorporates exactly one-half of that model (the half that computes upper bounds on delays). This model also apparently does not contain some of the desirable computer-related features of Model A2.2 that make the latter very efficient and easy-to-use.

MODEL A2.4

1. Primary Model Category: Delay-Oriented Runway Models
2. Reports Used to Evaluate the Model:
  - i) Title: A Simulation Model for Estimating Airport Terminal Area Throughput and Delays  
Author: Judith F. Gilsinn  
Agency: U.S. Department of Commerce, National Bureau of Standards  
Report #: FAA-RD-71-9  
Date: May 1971  
Other I.D.: NTIS # AD 745 514 - Sponsored by FAA
  - ii) Title: Validation of Maximum Airport Throughput Levels Estimated by the DELCAP Simulation Model  
Author: Judith F. Gilsinn  
Report #: FAA-RD-75-66  
Date: January 1975  
Other I.D.: NTIS # AD/A-011 485 - Sponsored by FAA
  - iii) Title: Validation of the DELCAP Airport Simulation Model  
Author: Judith F. Gilsinn  
Agency: U.S. Department of Commerce, National Bureau of Standards  
Report #: FAA-RD-75-154  
Date: July 1975  
Other I.D.: NTIS # AD-A021 127 - Sponsored by FAA
  - iv) Title: Validation of an Airport Simulation Model  
Author: Judith F. Gilsinn  
Agency: U.S. Department of Commerce, National Bureau of Standards  
Report #: NBS-10592  
Date: 1976  
Other I.D.: None
3. Reviewer's Summary: The above reports document a simulation model (DELCAP) designed to estimate airport throughput capacity



and aircraft delays, taking into account their dependence on (1) the traffic level and mix of aircraft types, (2) the airport configuration, and (3) the separation rules in force. The model is implemented in two parts: a preprocessor to facilitate data entry by providing standard data inputs which a user may elect instead of providing his own; and an event-oriented simulation model. The reports include a discussion of the elements in the airport system which are modeled, a description of the simulation model's logic and a set of sample outputs. Listings of the computer programs and a user's guide appear as appendixes.

Several instances in which the DELCAP model was exercised for the purpose of validation (with respect to both of its outputs--capacity and delay) are presented. Airport throughput capacity levels are calculated via DELCAP for five runway configurations, with three or four appropriate operating policies chosen for each, and for three different mixes of aircraft types. These estimates from DELCAP agree well (generally within 6 to 8 percent) with empirical values provided by the FAA. An attempt at validating DELCAP's delay-oriented outputs, using existing data on scheduled and actual times of aircraft departures and arrivals is also reported. It proved unsuccessful, because available data are not sufficient to isolate that portion of total delay which DELCAP is designed to measure (i.e., terminal area ATC delay). A data collection project to accumulate the data necessary for such validation is suggested.

#### 4. Model Description:

4.1 Model Type: Simulation; probabilistic.

4.2 Factors of National Airspace System Related to Model: Investigates the effects of airport runway configuration, aircraft mix and separation rules on capacity and delay.

4.3 Input Data Requirements: Characteristics of aircraft types (e.g., landing and takeoff speeds, runway occupancy times etc.), mix of aircraft types, traffic levels (described either by a complete

listing of arriving and departing flights, or by expected traffic levels per hour or by a combination of both), separation rules describing the distances between aircraft required by FAA regulations, description of the airport configuration, and airport operating policy (describing which runways handle landings only, takeoffs only, landings and takeoffs, and the method of sequencing operations).

4.4 Outputs Obtainable: Hourly capacity and daily delay profile for landings, takeoffs and for all aircraft.

5. Computer-Related Characteristics: The program is written in the simulation language SIMSCRIPT I.5 and is operational on a UNIVAC 1108 computer at NBS. Implementation of the model on other machines is easy. For the user's convenience, a FORTRAN pre-processing program has also been prepared and input is accepted in FORTRAN. It takes about 12 seconds of execution time to simulate a day's activity at a major airport.

6. Major Assumptions: Throughput capacity is defined as the number of operations achievable from a given distribution of traffic over the day. Aircraft arrive in either a random (i.e., Poisson) or deterministic manner. Landing aircraft enter the system at hand-off to the local controller and leave the system when they turn off the runway. Departing aircraft enter the simulation about 15 minutes before scheduled departure time. For landing operations, a minimum separation of 5 miles is required if non-heavy follows a heavy, 4 miles if a heavy follows a heavy and 3 miles for all other combinations. In takeoff operations, a 2-minute separation is required if non-heavy follows a heavy, 30 seconds for all other combinations. The user has the choice of inputting different separation standards. DELCAP does not simulate activities on the ground or in the terminal building, except for movements on the runways and for those taxiing operations which could affect airborne movement. Delay is defined as the difference between scheduled and actual times of operations.

7. Status of Model: No information is provided on whether this model has been used in connection with a specific project.

8. Quality of Documentation: The model's logic and assumptions are described in detail with flow charts. Complete listings of the preprocessor and the simulation programs are presented. Input formats and user instructions are presented in the appendixes.
9. Extent of Model Validation: DELCAP has been run using a variety of operating policies and runway configurations. Capacity results obtained from the simulation are in close agreement with the theoretical values calculated by the FAA's Air Traffic Service using a manual simulation process. Simulated delays, when compared with actual delays, proved to be much smaller since the model does not include the effects of non-ATC-related delays such as those due to gate congestion, crew actions, weather delays, mechanical problems, etc. However, the shapes of the distributions of simulated and actual delays were similar.
10. Modularity and Flexibility: The model can be used for a large variety of runway configurations, operating policies, and aircraft mixes to compute airport capacity and delays.
11. Evaluation: DELCAP combines a runway capacity and a runway delay model and is one of the two or three best models available in this category. Its logic and assumptions are well-documented and reasonable. It is clear that the model should perform well for airports with relatively simple runway configurations. It is less clear how the model would perform with complex airports and runway operating strategies. The quality of the inputs will obviously be critical in these latter cases. DELCAP, being a simulation, would also be expected to exhibit all the usual problems regarding the statistical significance of its results inherent in all simulation programs. This latter question has not been extensively addressed in the reports that were read.

The use of DELCAP for airport capacity and delay analysis is recommended.



## MODEL A2.5

1. Primary Model Category: Delay-Oriented Runway Models

2. Report Used to Evaluate the Model:

Title: Descriptions of the AIRSIM, CAPACITY and GOSIM  
Computer Programs

Author: Anonymous

Agency: The Boeing Company

Report #: Unpublished Document (Private Communication)

Date: Undated

Other I.D.: None

3. Reviewer's Summary: The airfield operations simulation (AIRSIM) program is a fast-time simulation of aircraft landing at or taking-off from an airport under various ATC operational rules. The program assesses the amount of delay to aircraft using the runways under different ATC managerial procedures and traffic loads. The program accepts and is sensitive to the following parameters: hourly schedules; within-hour schedules; aircraft type; time intervals between operations; magnitude of navigation errors on final approach; lateness distributions; air traffic control rules. The outputs provide delay data such as hourly or daily delay tables and annual delay statistics. In addition, information is provided on average delays, percent of delays sustained by landings and by takeoffs, fractions of time when airport facilities are utilized, and maximum queue lengths.

4. Model Description:

4.1 Model Type: Simulation; probabilistic

4.2 Factors of National Airspace System Related to Model: Investigates the effects of airport runway configurations, aircraft mix and separation rules on capacity and delay.

4.3 Input Data Requirements: Hourly traffic totals; within-hour traffic description; number of aircraft types; priority rules for sequencing runway operations by type of aircraft and by type of operation; schedule-keeping accuracy (lateness distribution);

matrices for the required minimum separations between all types of operations; standard deviations of separations between all types of operations; ATC queueing rules.

4.4 Outputs Obtainable: A large number of options is available on outputs related to the progress of the simulation run and to the delays suffered by airport users. These outputs include detailed tables listing hourly, daily and annual delays by type of operation, as well as average delays, maximum queue lengths observed during the simulation, etc.

5. Computer-Related Characteristics: No information is available on computer language, typical running times, core storage requirements, etc. (Macro) Flow charts for AIRSIM (and its associated program, CAPACITY) are provided.

6. Major Assumptions: AIRSIM depends on the runway capacity program, CAPACITY, to provide time intervals between operations for runway movements. These times are critical to the operation of the program. AIRSIM generates aircraft and processes them using the CAPACITY-provided time intervals between operations. A normally distributed lateness distribution (with parameters specified by the user) is superimposed on the scheduled arrival times. Each new aircraft is assigned to that runway (if more than one of the runways is operating) which "has had the longest time to process the previous aircraft." Once an aircraft is assigned to a runway, no reassignment can take place.

7. Status of Model: The model is claimed to be operational with a "validation run" using Chicago O'Hare Airport as the test case, having been completed.

8. Quality of Documentation: The documentation available to the reviewers was very limited and often vague, consisting essentially of a brief description of the model's logic and of a series of (Macro) flow charts.

9. Extent of Model Validation: A validation has been attempted for Chicago O'Hare Airport through estimation of annual delay statistics and subsequent comparison with United Airlines and O'Hare

Task Force delay estimates. Good agreement is claimed, but close examination raises serious questions as to the validity of the test.

10. Modularity and Flexibility: The model is modular and appears quite flexible with respect to the options available to the user. In particular, the important subprogram CAPACITY seems to be carefully designed from this point of view.

11. Evaluation: AIRSIM (and its subprogram CAPACITY) appear to be sufficiently sophisticated and powerful to rank among the better available delay-oriented simulation models. This assessment, however, is only a very tentative one due to the scarcity and poor quality of the information available to the reviewers. The true capabilities of AIRSIM (e.g., how many active runways can be handled simultaneously?) are also unclear from the available narrative. AIRSIM can thus be recommended as a model to be "looked into" by potential users, but no statement can be made, based on the information available to reviewers, on how good the model actually is.



## MODEL A2.6

1. Primary Model Category: Delay-Oriented Runway Models
2. Report Used to Evaluate the Model:

Title: A Simulation Model for Calculating Annual Congestion  
Delay Arising from Airport Runway Operations

Author: M. J. Attack

Agency: RTM Planning Partnership, Sydney, Australia

Report #: Journal of the Operational Research Society, Vol.  
29, No. 4, pp. 329-339

Date: August 1978

Other I.D.: None

3. Author's Abstract: This paper describes a simulation model of delays to aircraft caused by airport runway congestion. It was developed for the Australian Government as part of the Sydney Airport Project. Subsequently, it was used in a traffic management study of the airport which examined the scope of deferring the need for additional runway capacity by adopting administrative measures affecting runway utilization.

The model provides a means of estimating the effect on delays of major changes such as extra runways and/or increased demand at an airport or the operation of a planned new airport. It further provides the means to assess, for example, the effect of detailed changes in aircraft mix, runway operating modes, design of turnoffs or ATC procedures. It will operate on a general level or can examine the interaction of detailed operating policy with such factors as expected weather conditions or local curfews. The model has been specifically designed to allow these options by changes in data and it is not necessary to alter any parts of the computer program.

4. Model Description:

4.1 Model Type: Simulation; probabilistic.

4.2 Factors of National Airspace System Related to Model: Investigates the effects of airport runway configuration, aircraft mix and ATC separation rules and operating strategies on aircraft delay.

4.3 Input Data Requirements: Demand distribution in "typical" 24-hour days; total demand on "typical" days to be simulated; distribution of weather (wind, weather ceiling) over a year; airport geometry; runway operating modes (configuration preferences with weather); allocation of aircraft to runways; traffic generation schedule; aircraft-related data; priority rules for runway use.

4.4 Outputs Obtainable: A large variety of delay-related and facility utilization-related analyses can be produced for each typical day simulated. These include the number of operations per active runway, average daily and annual delay, delay in IFR weather, etc. Most outputs are optional at the discretion of program users.

5. Computer-Related Characteristics: The model was initially run on a CDC6600 computer, requiring 40,000 words of core. It has since been run on IBM, PRIME and ICL machines. "It was found that run times did not vary by more than 5 percent with changes in the number of runways in the range one to six, but that they did vary with the number of aircraft movements. A total of 175,000 movements per annum took about 1 system (central processing unit) second per 24-hour period and 550,000 took about 2.5 system seconds." No information is provided on the computer language in which the program is written.

6. Major Assumptions: The assumptions discussed in connection with the model description serve, in effect, to provide the model user with a number of options. For instance, the user may assume that aircraft are generated according to a complete schedule of movements for a day - in which case the model user must provide such a schedule. Or, alternatively, it can be assumed that aircraft are sampled from a frequency distribution of movements throughout the day (typically on an hour-by-hour basis) by flight type, and by arrivals and departures. The model offers three alternative ways of sampling from such frequency distributions. In general, the

model does not seem to contain any major restrictive assumptions (see also "Quality of Documentation" below).

7. Status of Model: The model has been used extensively in a traffic management study of Sydney's Kingsford-Smith Airport, including examination of the effects of modifying the demand profile at the airport. It is also stated that "in the past 3 years, the model has been used for other airports and different runway configurations and operating modes."

8. Quality of Documentation: The technical paper reviewed is clearly and concisely written. However, the details of the simulation model's logic are not described, leaving several important points unexplained. No program listing was available for this review and no user's manual is mentioned in the technical paper.

9. Extent of Model Validation: An attempt has been made to validate the model using Kingsford-Smith Airport as a test case. There appears to be very good agreement between model delay estimates and actual delay statistics. Testing, however, was for only a limited number of hours, and some aspects of the validation procedure are left vague or raise questions. It is also reported that for closely-spaced parallel runways the delays predicted by the model agree well with delays predicted by the AIL, Airport Capacity Handbook (see Section 1.5 of Part II).

10. Modularity and Flexibility: The model seems to be very carefully designed in this respect, offering numerous options to the user and allowing for changes in the emphasis on the various questions that the model can help explore.

11. Evaluation: The simulation model reviewed here is clearly among the best available in this category. It contains several unique features such as the options that it offers for generating schedules of aircraft movements over the course of a day, and the explicit inclusion of an easy-to-use weather subprogram. Some aspects of the model logic, however, are only sketchily outlined and, therefore, could not be adequately evaluated. Also, the reported performance characteristics of the simulation (see Item 5 above) seem almost too good to be true. This latter



information raises some serious questions in the mind of this reviewer as to how precisely the simulation model handles each aircraft that it generates. Finally, the technical paper reviewed exhibits little concern for questions of statistical convergence, number of required replications, etc., for this simulation model.

### MODEL A3.1

1. Primary Model Category: Complete Airport Models

2. Reports Used to Evaluate the Model:

i) Title: Model Users' Manual for Airfield Capacity and Delay Models, Books 1 and 2

Author: Carl T. Ball

Agency: U.S. Department of Transportation, Federal Aviation Administration

Report #: FAA-RD-76-128

Date: November 1976

ii) Title: User's Manual, PMM & Co. Airfield Simulation Model

Author: Anonymous

Agency: Peat, Marwick, Mitchell & Co., San Mateo, California

Report #: None

Date: April 1977

Other I.D.: None

iii) Title: Technical Report on Airport Capacity and Delay Studies

Author: Anonymous

Agency: Douglas Aircraft Co., McDonnell Douglas Corp., Long Beach, California

Report #: FAA-RD-76-153

Date: June 1976

Other I.D.: Contract No. DOT-FA72WA-2897

3. Reviewer's Summary (excerpted from first of referenced documents): The Delay Simulation Model is a computer program for analyzing the movement of aircraft through an airport. The Delay Simulation Model (DSM) was developed to determine delay per aircraft, travel time, and flow rate information. The model simulates the movement of aircraft from the entry gate of the common approach path to the terminal gates and from the terminal gates to takeoff. It treats the airfield components as integrated parts of a system. It provides a method for simultaneously analyzing the total airfield, including the terminal airspace associated with the runways.

The DSM is a critical events model that employs Monte Carlo sampling techniques. It operates by tracing the path of each aircraft through space and time. The records of aircraft movements are processed by the model to produce desired outputs, including a detailed hourly delay summary for each component of the airport, total travel time, and flow rates. Because of the modular structure of the model, the total airfield or its individual components can be analyzed by manipulation of the model inputs.

#### 4. Model Description:

4.1 Model Type: Simulation; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates airport configuration, aircraft mix and characteristics, ATC separation rules and traffic demand levels to congestion and delay on the runway/taxiway/apron complex.

4.3 Input Data Requirements: The extensive list of data requirements can be summarized as follows: logistic inputs (number of runs/replications desired, level of output detail desired, simulation start and finish times); airfield layout description (network description through listing of taxiway segment data, runways, exit taxiways, gates, holding areas, general aviation basing areas); ATC separation standards; aircraft routing data (paths from each terminal gate to each active runway); aircraft parameters (approach speeds, taxiing velocities, runway occupancy times, exit taxiway utilization, gate service times); demand schedule data (arrival and departure times, gate assignments, runway assignments).

4.4 Outputs Obtainable: Normal outputs include: average delay and total travel times through the airport for arrivals and departures for each hour of the simulation run, and by location on the airport; flow rates for each hour of the run and by location on the airport; and average delay per taxiway and runway network link. Some output options are available, such as separate outputs for each replication of the simulation (i.e., for each random number seed).

5. Computer-Related Characteristics: The simulation model is written in FORTRAN. It has a core requirement of approximately



490,000 (octal) words of storage. The model currently resides on a CDC CYBER 70/76 computer. The cost of computer runs obviously varies with the size and complexity of the simulated airport.

Typical costs are in the range of \$60 to \$100 for simulating, for a given set of inputs, about 4 hours of real time at a busy commercial airport (10 replications are used in these runs).

6. Major Assumptions: DSM has been developed under an extensive set of assumptions, including the following:

- a) A time schedule for arrivals and departures must be provided (the model does not have a schedule generating capability of its own). The model can superimpose a lateness distribution (on a probabilistic basis) on these scheduled times. General aviation flights, if any, must also be included in the schedule.
- b) Aircraft must be assigned to arrival runways as part of the input process. The model does not have a capability of its own for assigning aircraft to runways.
- c) A unique path must be specified between each active arrival runway and each terminal gate (for landings) and between each terminal gate and each takeoff runway (for departures). If a portion of that path becomes congested during the simulation run, the model does not provide an alternative path to bypass the congestion points.
- d) Arrivals have priority for use of the runways. However, separations between successive arrivals can be increased (to allow one or more departures between each pair of landings) whenever the takeoff queue exceeds a critical, user-specified value. Runway crossings have the lowest priority for use of the runways.
- e) The airfield is represented by a network of links and nodes. Each link can hold only one aircraft at a time. A typical example of an airport layout as represented by DSM is shown in Figure 1 (taken from the first of the documents referenced above). The limitation of link capacity to one

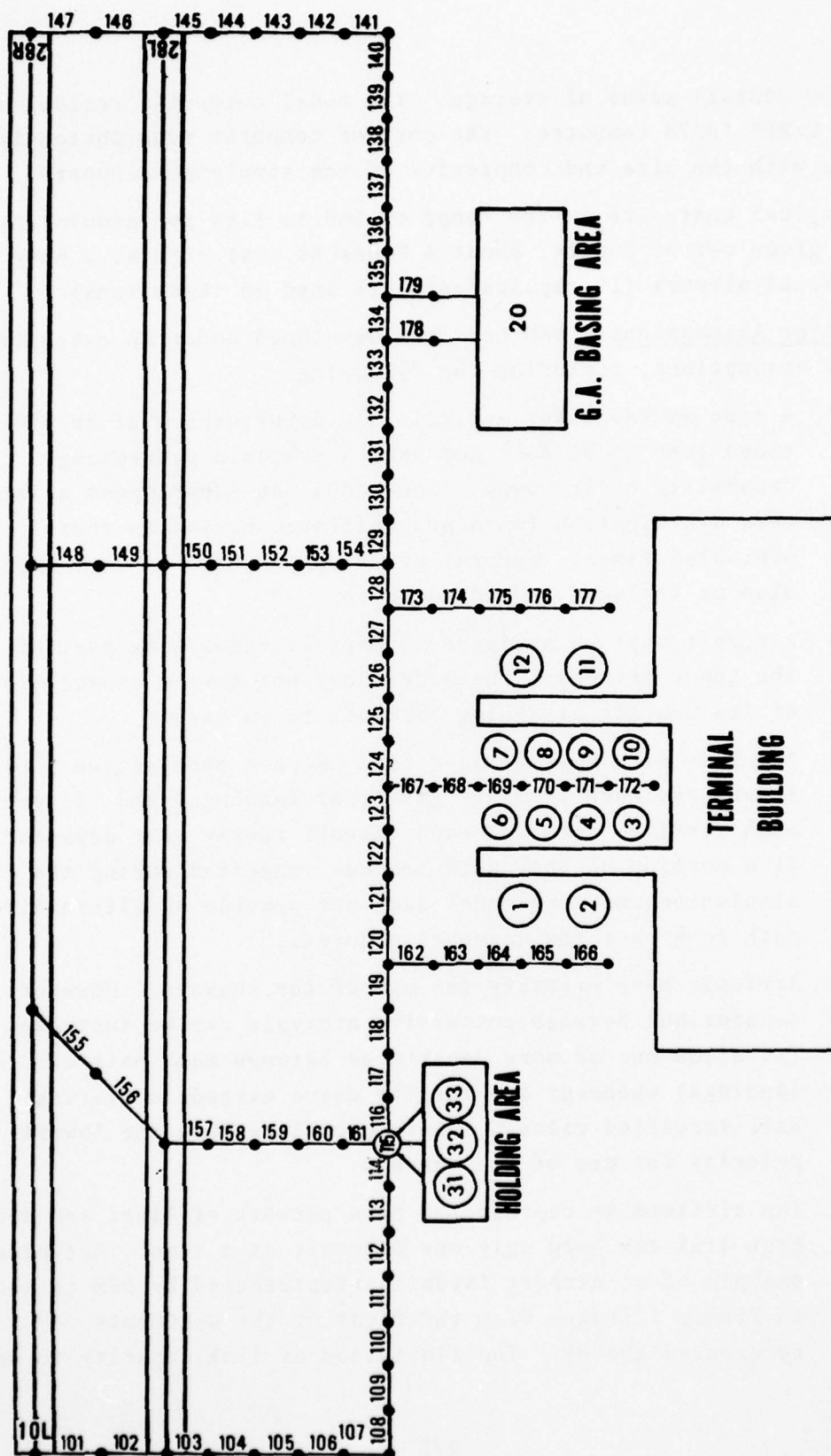


FIGURE 1. SAMPLE LINK-NODE DIAGRAM

aircraft requires short link lengths for a realistic representation of taxiway networks.

- f) All continuous random variables used by DSM have normal (Gaussian) distribution.
- g) All required inter-operation separations as dictated by ATC (for all possible active runway configurations) must be specified as inputs. The model does not estimate the required separations (on the basis of the airport geometry and a standard set of ATC rules).
- h) The model, unless otherwise specified, assumes that 10 replications of the simulation are sufficient to provide statistically reliable results - for each given set of inputs.

7. Status of the Model: At the time of this review the model is undergoing changes to improve some of its features and to correct some aspects of its logic. The model is being used in connection with the work of the Delay Task Forces that the Federal Aviation Administration has created for recommending improvements at several major airports in the United States.

8. Quality of Documentation: Although voluminous, the available documentation is often confusing and occasionally misleading. For instance, although reference is made to a model capability of "analyzing the terminal airspace associated with the runways," no such capability exists. Descriptions of the program's logic and definitions of the input parameters are also often vague and incomplete.

9. Extent of Model Validation: The third of the referenced documents describes an effort to validate the DSM at three airports (Chicago-O'Hare, Dallas Love Field, and Orange Country Airport--Santa Ana). Although it is stated that "the validation process demonstrated that the models yielded aircraft flow rates and travel times within the desired  $\pm 15\%$  of observed values," closer examination reveals that this is based on very weak grounds, particularly with respect to validation of aircraft delays.

10. Modularity and Flexibility: When used skillfully the model provides some degree of modularity and flexibility. Due to the



length of the computer code for the model, the fact that it is the end result of several revisions, and the lack of such features as comment cards, mnemonic variable names, etc., it has become difficult at this stage to make changes in DSM that would deviate from some of the more limiting program assumptions. An important feature of the model is the fact that it can be run without the taxiway/apron portion.

11. Evaluation: The Delay Simulation Model together with Model A3.2 represent the two most detailed and sophisticated airport simulation packages encountered in this review. DSM is capable of simulating 5 active runways simultaneously, a population of up to 200 aircraft, and an airport network consisting of up to 600 links and 1400 active gate-to-runway paths.

On the other hand, DSM has several undesirable features:

- a) The fundamental concept in the logic of the model is the representation of the airfield through a large set of links, each of which can hold only one aircraft at a time. This makes the simulation inefficient and expensive since critical events (entering or leaving a link) occur very frequently, causing the simulation to advance slowly through time.
- b) The part of DSM that simulates runway operations is relatively unsophisticated in comparison to the part that simulates taxiway operations. The internal logic of this part of the model is limited and requires that the user provide very detailed inputs on separations between operations on the same runway or on different runways. The model's emphasis is misplaced since most of the delay problems at airports are associated with the runways, not the taxiways.
- c) Extensive effort is required for preparation of inputs related to:
  - i) Airport geometry: We estimate, for example, that 5500 paths, each consisting of an average of about 20

links, would be needed to describe the taxiway network at O'Hare Airport.

- ii) Schedule of operations: an aircraft-by-aircraft time schedule is required.
- d) Over-estimation of taxiway congestion may result from the assignment of a unique path to each runway-gate pair. Whereas in practice the ground controller routes aircraft away from congestion points on the taxiway network (if possible), no such flexibility exists in DSM.
- e) Ten replications are recommended for each simulated case but the model outputs do not indicate the degree of statistical confidence that can be placed on the results. For many practical cases, ten replications of a simulation run will be inadequate to assure statistical convergence.

In summary, this model is the most detailed and generally adaptable of the publicly available airport simulation packages.\* However, it is our assessment that DSM should be used only in cases when a very detailed analysis of both runway and taxiway operations is desired. The prospective user should be aware of the model's limitations, the large amount of input data required, and the high learning and computing costs associated with the use of this model.

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\*The model's development has been funded by the Federal Aviation Administration so that at least one version of the model can be accessed through the FAA. (By contrast, Model A3.2 is the property of The Boeing Company.)

### MODEL A3.2

1. Primary Model Category: Complete Airport Models
2. Report Used to Evaluate the Model:

Title: Descriptions of the AIRSIM, CAPACITY and GOSIM  
Computer Programs

Author: Anonymous

Agency: The Boeing Company

Report #: Unpublished document - private communication

Date: Undated

Other I.D.: None

3. Reviewer's Summary (excerpted from referenced document): The Ground Operations Simulation (GOSIM) is a fast-time simulation program designed to model aircraft operations within the airport runway/taxiway/apron system. The program uses detailed airport geometry data, traffic demand data, aircraft performance data, and ATC operating rules to simulate the movement of aircraft on runways, in the taxiway network and in the apron/gate area.

The basic logic of GOSIM determines the type of operation that is to occur next by searching an event time array and an aircraft status array. An event time is any discrete time during the simulation when action must be taken to process an aircraft through the airport network. This may involve an aircraft reaching the end of a taxiway segment or intersection, arriving at or pushing back from a gate, or landing on or departing from a runway. There are five basic types of events: taxi operations; gate operations; runway operations; holding apron operations; and towing operations.

The program outputs provide statistics on a system-wide, segment-related and gate-related basis. Outputs include the number of conflicts, arrival and departure delay, delay as a function of airline and aircraft type, and airport throughput for the period simulated. By appropriately varying the required inputs, GOSIM can evaluate the effects of changes in airfield



routing logic, runway usage, aircraft fleet characteristics, airport configuration, and ATC performance characteristics.

#### 4. Model Description:

4.1 Model Type: Simulation; probabilistic

4.2 Factors of National Airspace System Related To Model: Relates airport configuration, aircraft mix and characteristics, ATC separation rules, and traffic demand levels to congestion and delay on the airport runway/taxiway/apron system.

4.3 Input Data Requirements: Data requirements are extensive due to the high level of detail of the simulation. They include airport geometry data, aircraft performance data, ATC separation and operating rules, and aircraft scheduling data. Geometry data include descriptions of taxiway/apron segments in terms of length and average speed in the segment, definitions of intersections by turn angle and radius of curvature, aircraft routings between gates, hangars, holding aprons and runways. Aircraft performance data consist of landing speeds, runway accelerations and decelerations, takeoff speeds, gate occupancy times, minimum gate service time requirements, etc. Traffic generation inputs can be of two types: sampling from various families of probability distributions for the length of the intervals between successive arrivals to the airport, aircraft types, airline assignment and runway usage; or a discrete traffic list supplied by the user that provides schedule times, airline, aircraft type and gate assignment for each aircraft.

4.4 Outputs Obtainable: Output statistics include total conflicts, total arrival and departure delay, delay as a function of airline and aircraft type, and total airport throughput. These outputs are reported by the hour and cumulatively, for up to 24-hour periods. Segment-specific, gate-specific, and holding apron-specific outputs and usage, occupancies and arrival and departure delays are also provided. In addition to these basic outputs, a large number of options exist for three additional levels of more detailed outputs.

5. Computer-Related Characteristics: No information is provided in the document reviewed on computer language, typical running times, core storage requirements, etc., for GOSIM. The simulations program clearly falls in the category of "event-paced" simulations in terms of how time is incremented. A total of 34 "macroflow" charts are provided for GOSIM. Two versions of the simulation exist: GOSIM 1 generates traffic through sampling from probability distributions, whereas GOSIM 2 requires a detailed time schedule as a traffic generating input.

6. Major Assumptions: The GOSIM description available to the reviewers was not sufficiently detailed to provide a basis for identifying limiting assumptions. The simulation designers have apparently made a major effort to avoid placing any major restrictive assumptions on the logic of the simulation.

7. Status of the Model: The model is claimed to be operational. No information is provided on any specific applications or work performed with GOSIM.

8. Quality of Documentation: The documentation available to the reviewers was very limited and quite vague, consisting essentially of a brief description of the model's logic and of a series of macroflow charts.

9. Extent of Model Validation: No information is provided on any attempt to validate the model with actual field data.

10. Modularity and Flexibility: The design of the GOSIM package seems to be both modular and flexible. An impressive number of options are claimed to be available.

11. Evaluation: It is difficult to evaluate the GOSIM model on the basis of available information (see item 8 above). Although the model is called a Ground Operations simulation, it actually appears to be considerably more than that, since it includes a logical package for simulating runway operations from final approach to runway exit (for arrivals) and from runway turn-on to the (airborne) departure hand-off point (for takeoffs). The simulation is capable of handling airports with up to 5 (active?)

runways and up to 100 aircraft gates.

The available limited description of the program's logic indicates that GOSIM offers several desirable features. For instance, aircraft are not confined to a single taxiing path for each runway-gate pair (unlike Model A3.1) and thus aircraft can be routed through the taxiway network on an individual basis to avoid congestion points. GOSIM also can apparently store more than one aircraft in runway, taxiway, or apron segments, a feature beneficial to the efficiency of the model with regard to computer running times. The model is also claimed to be capable of simulating airport operations to an unusually high level of detail (e.g., it includes simulating of the towing of aircraft to hangars!).

Unfortunately, there is no evidence that the model has been exercised to any considerable extent. The current status of the model is also unclear from the documentation available for this review. Therefore, while GOSIM appears to be a powerful and interesting simulation model, a more conclusive evaluation cannot be made without further information.



### MODEL A3.3

1. Primary Model Category: Complete Airport Models

2. Report Used to Evaluate the Model:

Title: Evaluation of Airfield Performance by Simulation

Author: A. E. Brant, Jr., and P. J. McAward, Jr.

Agency: Tippetts-Abbett-McCarthy-Stratton (TAMS), New York, NY

Report #: Transportation Engineering Journal, Vol. 100, No. 2,  
pp. 505-522

Date: May 1974

Other I.D.: None

3. Reviewer's Summary: A complete airport simulation model was developed and used by TAMS to evaluate the proposed layout plan of the Dallas-Fort Worth Regional Airport at the time when this airport was still under construction. The model simulates aircraft movements from the beginning of the final approach to the terminal gate, and then from the gate through the taxiway network to takeoff. Three phases in the development of the airport (the 1975, 1985 and "ultimate" layout plans) were simulated. The model classifies aircraft into 4 distinct categories (according to aircraft size) and compiles statistics on delays for each type of aircraft and on utilization of runways, runway exits, gates, and taxiways. Estimates of delay costs are also calculated taking into account aircraft cost per minute and value of passenger time. In addition to these measures of performance, visual display of the simulation is provided by a 10-minute, computer-generated motion picture of selected portions of the simulated airport activity.

4. Model Description:

4.1 Model Type: Simulation; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates airport layout, aircraft mix and characteristics, ATC separation rules and traffic demand levels to delay and delay costs on the runway/taxiway/apron system.

4.3 Input Data Requirements: Airport layout plans including location of runways, turnoffs, taxiways, aprons, gates, and maintenance and cargo areas; flight schedules including type of flight, arrival and departure flight corridor, airline and terminal gate-group destination; aircraft characteristics such as landing and taxiing speeds, gate service times, average takeoff distance, and delay cost per minute; control procedures for sequencing landings, departures, and runway crossings by taxiing aircraft; and environmental conditions such as weather (IFR-VFR) and wind direction.

4.4 Outputs Obtainable: Total travel time of aircraft through airport complex; delays and queue lengths by type of aircraft and by airport location; runway, turnoff, gate and taxiway segment utilization. A motion picture display of "selected portions of the simulated future activity" has also been prepared.

5. Computer-Related Characteristics: No information is provided in the document reviewed on typical running times, program length, core storage requirements, etc. The simulation is written in GPSS and is, therefore, of the event-paced type.

6. Major Assumptions: A time schedule of flights is required as input (the program does not generate a schedule of its own); time gaps between successive arrivals over the runway threshold appear to be deterministic (constant) and depend only on the types of the two aircraft in each pair (16 possible pairings); landings have priority over departures whenever a runway is used for both types of operations. The model description is not sufficiently detailed to provide the basis for identifying other limiting assumptions, if any.

7. Status of the Model: It is stated that "minor modifications" in the Dallas-Fort Worth Regional Airport layout, resulting from analysis using the simulation model results, led to construction cost savings of over \$1,000,000. No information is provided as to whether this model has been used in other projects.

8. Quality of Documentation: The paper reviewed provides only

a very limited and vague description of the simulation model. The discussion of the model's logic is also ambiguous: it is not clear what features the model actually contains - as opposed to what features it would contain, ideally.

9. Extent of Model Validation: A "logic validation" was apparently performed by ascertaining that the model behaved as expected in various types of specific situations. There is no mention of any attempt to validate model outputs against actual airfield data.

10. Modularity and Flexibility: No discussion of available options or of modular features is provided in the reviewed document. It would appear that the model's emphasis is on developing a location-specific rather than a generally adaptable tool.

11. Evaluation: Due to the limited amount of information available on this model, all conclusions in this evaluation must be labelled as "tentative." It seems clear, however, that the model lacks much of the sophistication and the features of Models A3.1 and A3.2. For instance, the available model description does not address such important issues as adaptability to different airport layouts, statistical convergence and validation of the outputs, modeling of probabilistic phenomena, and alternative operation-sequencing strategies. It is also not clear from the model description that the simulation actually uses all of the rather detailed input data described under item 4.3 above.

This model, which was apparently developed in the late 1960's, may have been a pioneering effort at the time but has rather obviously been superseded by later simulation models such as A3.1 and A3.2.



#### MODEL A3.4

1. Primary Model Category: Complete Airport Models

2. Reports Used to Evaluate the Model:

i) Title: The Airport Performance Model, Vol. I and II

Authors: J. F. Bellantoni, H. M. Condell, I. Englander,  
L. A. Fuertes, J. C. Schwenk

Agency: U.S. Department of Transportation, Transportation  
Systems Center

Report #: FAA-ASP-78-10, I & II

Date: October 1978

Other I.D.: None

ii) Title: The Airport Performance Model

Authors: D. Hiatt, S. Gordon, J. Olesen

Agency: U.S. Department of Transportation, Transportation  
Systems Center

Report #: FAA-ASP-75-5

Date: April 1976

Other I.D.: None

3. Reviewer's Summary: The Airport Performance Model (APM) is a simulation of the movement of aircraft, passengers and airport access vehicles at an airport. Passenger and airport access vehicle movements are examined in the landside portion of APM, which is not the subject of this review. The airside portion of APM consists of (1) a demand module that generates the number and time distribution of aircraft arrivals and departures, and the aircraft fleet mix and weather conditions to be simulated; (2) a runway module which is concerned with estimating aircraft delays at the runway portion of the airfield; (3) a gate module which is similarly concerned with aircraft gate delays; (4) an energy consumption/air pollution module which uses the normal levels of airside operations, as well as the runway and gate delays computed earlier, to provide estimates of energy consumption and air pollution emissions for airside operations; and (5) a cost module that converts air and ground delays experienced by aircraft to

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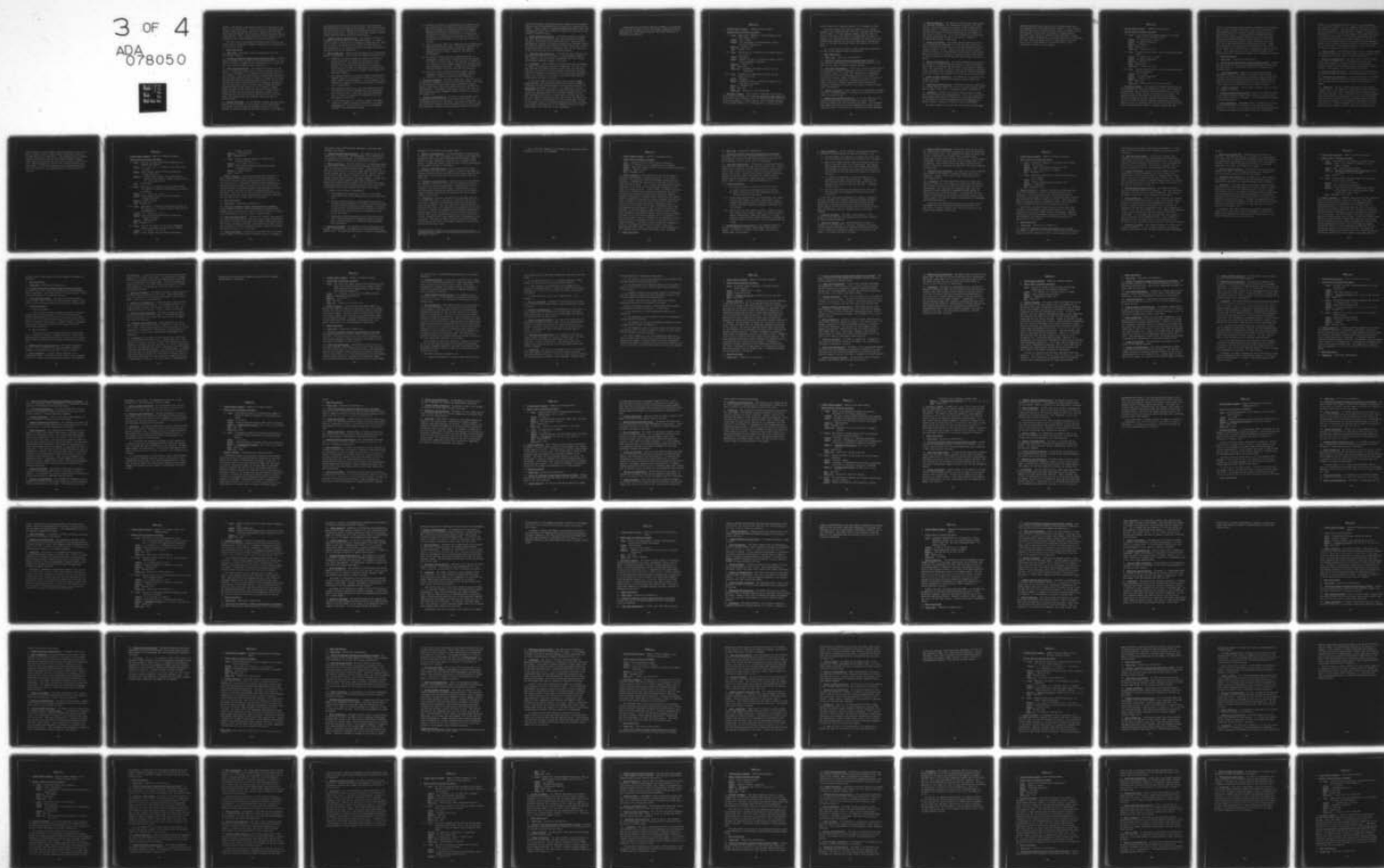
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dollars. The APM has a data base for each of 31 high density airports in the United States. It can be run in an interactive mode so that a user may override some of the inputs in the data base (and substitute another set of inputs), and also choose the desired output options. APM, in addition to daily delay statistics, also includes an option that computes annual delay statistics.

The first of the two documents referenced above describes the latest version of APM which expands considerably on the capabilities of the earlier version.

#### 4. Model Description:

4.1 Model Type: Simulation; mostly deterministic with some probabilistic aspects.

4.2 Factors of National Airspace System Related to Model: Relates airport configuration, aircraft mix and characteristics, level and time-distribution of demand and ATC separation rules to delay, delay costs, energy consumption and air pollution.

4.3 Input Data Requirements: APM requires an extensive set of inputs. It contains a data base for 31 major airports that offers the user an opportunity to use internally stored input values if he so chooses. Input data requirements include airport identifier; type of analysis desired (daily or annual); average traffic volume (in operations per day or operations per year by air carrier, air taxi and GA); hourly demand profiles (for commercial and general aviation operations); mix of aircraft types; maximum achievable processing rates on the runways by type of weather; assumed weather category by hour of the day (for daily analysis only); delay costs per unit of time for passengers; aircraft direct operating costs; aircraft pollution emission levels by aircraft type; radar-approach spacing standards; number and types of terminal gates.

4.4 Outputs Obtainable: For the takeoff, landing, and gate queues, outputs can be provided on a total daily or total annual basis and include: aircraft hours and passenger hours lost in queue; increase in aircraft operating costs due to delays; cost of passen-



ger time lost due to delays; and excess pounds of hydrocarbons, carbon monoxide, and nitrogen oxides emitted. More detailed delay statistics such as mean, maximum and minimum queue size by time of day are also provided. (The model also provides landside related outputs which are not of concern to this review.)

5. Computer-Related Characteristics: The program is written in FORTRAN IV and is available on a time-shared basis. It resides on the TSC PDP-10 (DEC system-10) computer in Cambridge, MA. Data for 31 airports are stored on disk at the TSC PDP-10 facility. APM incorporates a user-interactive input and output specification procedure prior to each program run.

6. Major Assumptions: APM has been developed with a considerable number of assumptions. Some of the more important among them are:

- a) Commercial aircraft schedules are based on the Official Airline Guide and are specified via minute-by-minute demand profiles. No lateness distribution or other probabilistic deviations are applied to this schedule. General aviation flights are distributed uniformly within each 30-minute interval and are added to the schedule of commercial flights.
- b) The combined capacity of any given runway configuration is computed before a run and then is treated as if it were a single runway with that capacity. As a consequence, from the model's viewpoint, arrivals and departures are merged into a single queue.
- c) Inter-operation times (e.g., the time separation between two successive arrivals) depend solely on the lead and trail aircraft types. Once these times are determined they are treated as constants (non-probabilistic) for each given aircraft pair.
- d) A "calibration term,"  $\alpha$ , is used to "adjust" the runway capacity to changes in weather conditions or in runway configurations. The derivation of  $\alpha$  is not adequately explained in the documents reviewed.

- e) Arrivals of aircraft at terminal gates are treated as random (Poisson) and the durations of service times at the gates are assumed to be random variables with negative exponential probability distributions. It is further assumed that all gates are shared by all airlines, but the number of available gates is reduced to "adjust" for the fact that each airline, in practice, has its own set of gates.
- f) The aircraft gate delays are computed by using steady-state formulae from queueing theory, specifically formulae for M/M/s queueing systems (=Poisson arrivals, negative exponential service times, s parallel and identical servers/gates).
- g) By contrast, runway delays are computed from what is essentially a deterministic simulation (once the schedule of flights is given), that is, the schedule of flights is run, aircraft land and depart spaced by the minimum acceptable separations, and delay is computed as the difference between scheduled and actual time for each operation.
- h) Unit delay costs, pollutant emission figures, energy consumption figures, and costs of passenger time are based on a variety of survey data and assumptions.

7. Status of the Model: The model already has a data base for 31 of the busiest commercial airports in the United States. The model has been applied to three actual airport investment problems (Detroit Metro Wayne, Charlotte Douglas Municipal, and Honolulu International). In addition, APM has been used as the basis of a model simulating delay propagation within a network of airports (see Model A7.3).

8. Quality of Documentation: The first of the documents referenced above describes the latest version of APM, and is the recommended reference for the model. The logic, assumptions, and use restrictions associated with the model are, for the most part, well presented. However, certain important aspects of the model

such as the capacity calibration and the computation of acceptance rates are not well explained and are likely to be confusing to the reader. A User's Manual, a Program Documentation report, and a Data Documentation report are included in Volume II of the first of the documents referenced above.

9. Extent of Model Validation: An attempt was made to validate the model against actual runway delay data observed at Kennedy, LaGuardia, and Newark airports during May 1972. Generally good agreement was obtained for Kennedy and Newark but the model results for LaGuardia differed significantly from the actual data. Closer examination, however, casts considerable doubt on the credibility of the field data used for the validation attempt.

10. Modularity and Flexibility: The model has been designed with modularity and flexibility in mind. It would appear, however, that changes in any of the major assumptions (see Item 1 above) would require important changes in the model.

11. Evaluation: APM is primarily oriented toward the performance of benefit-cost analyses of airport investments. As such, it is not concerned with predicting very accurate flow rate and delay statistics for each part of the airfield. Therefore, this model cannot be considered an alternative to other more detailed models such as A3.1 and A3.2, or to some of the better delay-oriented runway models reviewed in Section 2.

On the other hand, we believe that APM can provide runway delay estimates which should be sufficiently accurate to make it a valuable tool for the performance of cost-benefit analyses for large-scale investments in airports. By large-scale, we mean investments that will change the aircraft processing rates of the airport by a magnitude that will exceed APM's margin of error. This statement refers only to runway delays; we think that the gate delay model is unrealistic (see item 6 above) and should not be used. Special caution should also be exercised when setting the acceptance rates of the runway configurations (this, as noted, is an input to the model and is not computed internally by APM) because APM is very sensitive to this parameter.



Two particularly attractive features of APM are its extensive data base and its application to the energy consumption/pollution emission area. Both of these features are unique among all of the models reviewed here.

MODEL A3.5

1. Primary Model Category: Complete Airport Models

2. Reports Used to Evaluate the Model:

- i) Title: Model User's Manual for Airfield Capacity and Delay Models, Book 1.

Author: Carl T. Ball

Agency: U.S. Department of Transportation, Federal Aviation Administration

Report #: FAA-RD-76-128

Date: November 1976

- ii) Title: Procedures for Determination of Airport Capacity, Vol. I and II

Author: Anonymous

Agency: Douglas Aircraft Co., McDonnell Douglas Corporation, Long Beach, California

Report #: FAA-RD-73-11

Date: April 1973

Other I.D.: AD Number AD-763560; Contract No. DOT FA72WA-2897

- iii) Title: Techniques for Determining Airport Airside Capacity and Delay

Author: Anonymous

Agency: Douglas Aircraft Co., McDonnell Douglas Corp. Long Beach, California

Report #: FAA-RD-74-124

Date: June 1976

Other I.D.: Contract No. DOT FA72WA-2897

3. Reviewer's Summary: This review is concerned solely with a set of analytical models for computing taxiway and gate capacities. These models were developed as part of the project that also led to the development of a runway capacity model reviewed elsewhere in this report (Model A1.3). These models, in combination, pro-

vide the means for a capacity analysis of the complete airport.

The taxiway models deal with the capacity of (i) one-way taxiways; (ii) two-way taxiways; and (iii) taxiways intersecting active runways. The gate capacity models treat the cases in which (i) all gates are capable of accommodating all types of aircraft (ii) some gates cannot accommodate all types of aircraft. Another model examines the conditions under which limited apron space (in the gate area) might reduce the capacity of a set of gates.

All of the models are based on simple analytical expressions for the airport component under consideration.

#### 4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates aircraft characteristics, ATC ground separation rules, and gate service times to taxiway and gate capacity.

4.3 Input Data Requirements: Traffic mix; aircraft characteristics (taxiing speed, aircraft dimensions); gate service times by type of aircraft; types of aircraft that each gate can accommodate; ATC separation rules for permitting aircraft on a taxiway to cross active runways; number of operations per hour on the active runway, and mix of operations (landings and takeoffs) on the runway; distance of taxiway-runway intersection from runway threshold; configuration of apron area feeding the group of gates under consideration.

4.4 Outputs Obtainable: Hourly capacity (in the maximum throughput sense) of: a taxiway segment; a taxiway that intersects an active runway; a group of gates.

5. Computer-Related Characteristics: It is very simple to write computer programs that calculate numerical values from the analytical expressions that constitute the models. Such programs have apparently been written, and nomographs of taxiway and gate capacities under a wide variety of conditions have been developed.



6. Major Assumptions: The capacities obtained from these models are "maximum throughput" (or "saturation") capacities and thus assume a continuous presence of aircraft on the taxiways and at the gate areas. A random mix of aircraft types is assumed, i.e., aircraft are present in the same proportions as they appear in the airport's traffic mix. It is also assumed that aircraft will use any available gate as long as that gate is capable of accommodating aircraft of that type.

7. Status of the Model: The taxiway and gate models have been used to develop the nomographs of taxiway and gate capacities that are presented in the capacity and delay "Handbook" which was issued in 1976 by the FAA. (This is the third of the documents referenced above). The same Handbook also provides "delay curves" that can be used with the capacity estimates given by the models to obtain estimates of taxiway and gate access delays (see Item 11 below).

8. Quality of Documentation: The model documentation provided in the second of the reports referenced above is clear and adequate with respect to explaining the derivation of the capacity expressions. No explanation is offered in any of the documents reviewed on how the delay curves provided in the capacity and delay Handbook (see item 7 above) were derived in the case of taxiways and gates.

9. Extent of Model Validation: No information is provided on any attempt to validate the gate and taxiway capacity models with actual field data.

10. Modularity and Flexibility: The simple analytical expressions for taxiway and gate capacity are easy to use and to modify according to changes in the set of circumstances under consideration.

11. Evaluation: The gate and taxiway capacity models reviewed here are very simple and straightforward. Given the simplicity of the problems being solved, the models can be considered adequate for the purpose of providing approximate hourly capacities of groups of gates, taxiways, or taxiways intersecting runways.

The same, however, is not true for the taxiway and gate delay

estimates provided in the third of the references given above (the Handbook of airport capacities and delays). These estimates, based as they are on a family of delay curves (see Figure 2-68 in the Handbook), violate basic principles of queueing theory. Therefore, their validity, especially for cases where a large number of gates are available, is strongly doubted by the reviewers. For cases involving groups of five or more gates, use of the delay curves of the Handbook will probably result in over-estimation of delays by a wide margin.

MODEL A3.6

1. Primary Model Category: Complete Airport Models

2. Reports Used to Evaluate the Model:

- i) Title: A Preliminary Requirements Analysis for Airport Surface Traffic Control Systems

Authors: G. Baran and R. A. Bales

Agency: The MITRE Corporation

Report #: FAA-RD-73-6

Date: January 1973

Other I.D.: Contract RA-73-11

- ii) Title: Airport Surface Traffic Control Systems Deployment Analysis

Authors: G. Baran and R. A. Bales

Agency: The MITRE Corporation

Report #: FAA-RD-74-6

Date: January 1974

Other I.D.: Contract RA-73-11

- iii) Title: Airport Surface Traffic Control Systems Deployment Analysis-Expanded

Authors: R. A. Bales

Agency: The MITRE Corporation

Report #: FAA-RD-75-51

Date: March 1975

Other I.D.: Contract RA-73-11; AD No. A013579

3. Reviewer's Summary: The sequence of studies referenced above were performed as cost/benefit analyses to assess the advisability of deployment, and the optimal time of installation, of Airport Surface Traffic Control Systems at 39 major U.S. airports. The systems considered were ASDE-3 (an improved Airport Surface Detection Equipment) and ASE (Advanced Surveillance Equipment). To carry out the cost/benefit analysis an approximate analytical model was used for estimating the total level of delays associated with the taxiway/runway system. The model assumes that the



capacity of the taxiway-runway system is determined by the maximum rate at which the ground controller or the local controller, or both (depending on the situation at hand) can process aircraft (operations per hour). It assumes that oversaturated periods (when aircraft demand exceeds capacity) are succeeded by under-saturated periods (when demand is below capacity). The latter periods are assumed sufficiently long so that queues that have built up during oversaturation can now dissipate fully. Under these conditions two expressions for average delay per aircraft are developed, one for good visibility and one for poor visibility cases. These expressions are used in combination with future demand forecasts to produce the sought after cost/benefit estimates.

4. Model Description:

4.1 Model Type: Analytical; deterministic

4.2 Factors of National Airspace System Related to Model: Relates the type of airport surface surveillance equipment available, and the performance of local/ground controllers, to airport delays and delay costs.

4.3 Input Requirements: Capacity of runway/taxiway system expressed in terms of the number of operations per hour that can be processed by the ground/local controllers (capacity under poor and good visibility conditions must be given); demand levels by time of day; forecasted demand levels for future years; cost of delays expressed in terms of dollars per minute of delay.

4.4 Outputs Obtainable: Size of delays and delay costs, by year, at airports of interest.

5. Computer-Related Characteristics: This is an analytical model. A very simple computer program can be written to carry out the calculations described by the model. No discussion of this appears in the documentation.

6. Major Assumptions: The demand level is assumed to be distributed within each hour in the ratio of 1.3, during the peak 20 minutes of the hour, to 1, during the other 40 minutes of the hour. No overflow of demand from one hour to the next is permitted.

Instead it is assumed that when the ratio of capacity/demand for a given hour reaches 1.1 (i.e. demand is about 90% of capacity), any additional demand - resulting from long-term traffic growth - will be transferred to other peak hours. Demand is assumed to be deterministic, i.e., for any given demand rate, demand constitutes a steady flow of aircraft. Four possible "determining factors" are compared to see which one, if any, imposes the earliest (in terms of the forecasts) need for new surface detection equipment: ground control capacity in good visibility; local control capacity in good visibility; ground control capacity in poor visibility; local control capacity in poor visibility.

7. Status of Model: The referenced reports do not indicate whether this model has been used for purposes other than its original one, to determine the need for ASDE-3 or ASE at 39 airports.

8. Quality of Documentation: The logic used in the development of the various expressions is not always clear due to the occasionally ambiguous statement of some of the assumptions. Detailed examples of how calculations are performed for specific airports (which appear in the Appendixes) are helpful.

9. Extent of Model Validation: No information is provided on any attempt to validate any aspects of this model against field data.

10. Modularity and Flexibility: The expressions used to estimate delay are very general and can be used for other aspects of the NAS, provided that one accepts the premise of deterministic demand.

11. Evaluation: The most interesting aspect of the approach reviewed here is its attempt to include considerations related to surface traffic and to the ground controller in determining airport delays and delay costs. The model itself is overly simplistic, even after taking into consideration the fact that cost/benefit analyses usually require only very approximate delay estimates. For instance, because of the assumption of deterministic demand and the 1.3 to .1 "peak 20 minutes-to-low 40 minutes" ratio, no delay would be incurred as long as the level of demand in the

peak 20 minutes is even slightly below the capacity of the airport. This is clearly untrue in practice where large delays would be observed under such circumstances. The assumptions that no demand overflows to the next hour and that demand eventually spreads itself evenly over the day are also overly restrictive and artificial. While the questions raised in the referenced reports are interesting, it should be recognized that the approach described will yield only very crude approximations to the quantities of interest.



MODEL A4.1

1. Primary Model Category: Models of Terminal Airspace

2. Reports Used to Evaluate the Model:

- i) Title: Research in Ground-Based Near-Terminal Area 4D Guidance and Control  
Author: C. L. Britt, Jr., L. Credeur, C. M. Davis, and W. Capron  
Agency: NASA, Langley Research Center and Research Triangle Institute  
Report #: International Congress of the Aeronautical Sciences, 10th Congress, Ottawa, Canada, October 3-8, 1976, paper #76-57  
Date: October 1976
- ii) Title: Definition of a Terminal Area Air Traffic Model for Studies of Advanced Instrumentation and Control Techniques  
Authors: C. L. Britt, Jr., et al.  
Agency: NASA, Langley Research Center and Research Triangle Institute  
Report #: NASA-CR-111979  
Date: December 1971
- iii) Title: Development of Simulation Techniques Suitable for the Analysis of Air Traffic Control Situations and Instrumentation  
Authors: C. L. Britt, Jr., et al.  
Agency: NASA, Langley Research Center and Research Triangle Institute  
Report #: NASA-CR-112195  
Date: December 1972
- iv) Title: Study of the Impact of Air Traffic Management Systems on Advanced Aircraft Avionic Systems  
Authors: C. L. Britt, Jr., et al.  
Agency: NASA, Langley Research Center and Research

Triangle Institute

Report #: NASA-CR-132278

Date: February 1973

- v) Title: Vehicle Dependent Aspects of Terminal Area  
Guidance and Control

Authors: C. L. Britt, Jr., et al.

Agency: NASA, Langley Research Center and Research  
Triangle Institute

Report #: NASA-CR-144987

Date: June 1976

3. Author's Abstract: This paper describes work being done at NASA, Langley Research Center and at the Research Triangle Institute on advanced, ground-based guidance and control for the near terminal area. Large-scale computer traffic simulations in conjunction with a Boeing 737 aircraft will be used to evaluate various concepts for automated terminal area metering and spacing. The all-digital real-time air traffic simulation model is described. Facilities for aircraft tracking and for interfacing the aircraft with the digital simulation are discussed, along with possible application to other types of experiments.

4. Model Description:

4.1 Model Type: Simulation; probabilistic

4.2 Factors of National Airspace System Related to the Model:

Relates terminal area ATC rules and procedures, controller-pilot communications characteristics, and air traffic controller strategy to the performance of the ATC system in terminal areas.

4.3 Input Data Requirements: Aircraft mix; terminal area geometry (location of navigational aids and entry fixes, runway orientation); ATC-related information (description of nominal flight paths between entry fixes and runway thresholds, route geometry for path stretching, allowable air traffic controller actions, separation standards, checkpoint locations, etc.); wind data.

4.4 Outputs Obtainable: Statistics on delivery error to the outer marker; amount of control activity required; effects of communica-

tion delays; pilot workload delay statistics; time spent under terminal area control.

5. Computer-Related Characteristics: The computer code for the simulation is operational. The development of new capabilities is continuing. No information is reported on the cost of runs. No program listing is included in the documents reviewed.

6. Major Assumptions: With the exception of the bank angle logic, and the cockpit simulator which can be interfaced with the simulation, aircraft are treated as point masses. Longitudinal and vertical accelerations are selected, when required, from a set of discrete values specific to each aircraft type. Perfect information on the aircraft state is assumed to be available in the cockpit, except when an aircraft is being vectored. In this case, the deviation from the nominal flight path is modeled as a normally-distributed random variable with zero mean, and variance increasing linearly with time elapsed since the vector was given. Surveillance data include normally distributed error terms.

A specific ATC strategy is implemented:

- a) The sequencing of operations is done on a first-come, first-served basis with landings given priority over take-offs.
- b) For each landing aircraft a 4-dimensional flight path is selected from a predefined set of paths with expected times of arrival (ETA's) specified at each waypoint. In case of a conflict the aircraft whose ETA at the point of conflict is the earliest is given priority (irrespective of the ETA at the runway).
- c) Controller actions are assumed to occur only when an aircraft reaches prespecified checkpoints along its flight path. Increased realism is achieved by specifying many such checkpoints.

7. Status of the Model: The program is actively maintained and updated. Modifications and extensions are being implemented on a regular basis. The model has been used in a variety of experiments



documented in the reports listed under item 2.

8. Quality of Documentation: The documentation is extensive and, in general, good. Many flow charts are included in the supporting documents to facilitate the understanding of the model's logic. The various model assumptions, however, are not always clearly stated. A simulation manual, which provides a detailed description of the computer program, is available.

9. Extent of Model Validation: No validation of the primary model outputs (see Item 4.4) is reported. However, the number of landings processed during simulations of the Atlanta terminal area agrees well with the capacity of the Atlanta airport under IFR conditions.

10. Modularity and Flexibility: The model can be easily modified and expanded. Relatively little effort is required to adapt it to a specific terminal area geometry. Modifications of the ATC strategy in use require greater effort. Some functions (e.g., word packing\*) are computer architecture specific and may require extensive modifications before the model can be run on another computer installation.

11. Evaluation: The major contribution of this model consists of the algorithms that it contains for simulation the actions of air traffic controllers in the terminal area under current ATC rules and procedures. Thus, the model can be readily applied in evaluating the effects of varying traffic characteristics (aircraft mix, etc.), terminal area geometries, and separation standards on airport capacity and on delays to aircraft in the terminal area. Several such studies (including predictions of noise levels and of fuel consumption) have been conducted and are documented in the references. The amount of effort necessary to modify the model for testing new ATC rules and procedures depends on how different these are from current ones.

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\* Word packing is a technique for making more efficient use of available computer memory by storing more than one variable in the same memory location.

This is the most complete of the terminal area simulation models reviewed and its use is recommended.

## MODEL A4.2

1. Primary Model Category: Models of Terminal Airspace

2. Report Used to Evaluate the Model:

Title: Terminal Area Air Traffic Control Simulation

Author: H. Bernstein, A. B. Greenberg, and S. Sokolsky

Agency: NASA, Ames Research Center, and the Aerospace Corporation

Report #: NASA-CR-152017

Date: September 1976

3. Author's Abstract: The Terminal Area Air Traffic Control Simulation was designed to permit the analysis of air traffic movements in high density controlled airspace serving major air terminals, including the interactions of arriving aircraft with those waiting to depart. It is a large scale model permitting the simulation of all major (interacting) traffic movements in an arena in a single scenario. In this report, the model's inherent capability is demonstrated through the simultaneous analysis of the three major airports serving the New York area (Kennedy, LaGuardia and Newark). Arriving traffic examined by the computer program is generated some distance from the Terminal Control Area (TCA), although it is possible to generate pop-up traffic much closer to the final approach regions. Departing traffic is generated on the airport, but initially considered earlier than the announced desired departure time, to assist in mixing with arrivals. As arrivals approach their respective feeder fixes, their approaches are planned in detail, or they are held pending availability of a satisfactory approach slot. An approach is satisfactory when it meets a stringent set of separation criteria. Aircraft arrive at the feeder fix with a variety of errors in flight parameters. When these errors are observed, commands are issued in an attempt to improve each aircraft's path as it approaches the outer marker. Each aircraft's fuel consumption is also computed during the flight from feeder fix to touchdown.

4. Model Description:



4.1 Model Type: Simulation; probabilistic

4.2 Factors of National Airspace System Related to the Model:

The model relates ATC rules (minimum separations, etc.), errors in navigation, aircraft mix and traffic density to terminal area ATC performance, traffic delays and fuel consumption.

4.3 Input Data Requirements: Aircraft mix; aircraft performance characteristics (typical aircraft climb and descent rates, initial, terminal area, approach, and landing velocities, typical accelerations, feeder fix arrival errors, velocity errors, heading and descent rate errors); terminal area geometry (runway orientation, feeder fix and outer marker locations); Air Traffic Control minimum required separations; flight path data (ILS intercept ranges, angle of intercept, flight path geometry, etc.).

4.4 Outputs Obtainable:

- i) Main output: Summary of runway activity (by runway):
  - a) number of arrivals and departures on the runway
  - b) delay, holding time and fuel consumption for each aircraft which uses the runway.
- ii) Flight path generation data (for each output run): number of paths used; number of aircraft being held at fixes; changes from planned takeoff or landing times; number of rejected aircraft; deferred assignments; touchdown intervals planned.
- iii) System data (for each output interval): number of available communication channels; number of aircraft generated; number of departures, number and identity of aircraft passing the outer marker, number and nature of commands to aircraft, number and identity of aircraft removed from the system.

5. Computer-Related Characteristics: The computer program is written in FORTRAN and occupies approximately 500k bytes of memory. No listing is included in the report and no data on running times are available.

6. Major Assumptions: The ATC terminal area procedure simulated in the model is very different from the one currently in use:

- a) For each runway, the time axis is divided into slots, each slot representing a constant time interval (say, 2 minutes).
- b) When a new landing aircraft enters the terminal area, the earliest available time slot is identified. The computer then attempts to develop a feasible 4-dimensional flight path through the terminal area, such that the aircraft can be delivered at the runway threshold within the identified time slot.
- c) If a feasible flight path is found, the time slot is assigned to the newly arrived aircraft. Otherwise, the next available slot is identified and step b) above is repeated until finally a feasible time slot is assigned to the aircraft.
- d) Arrivals enjoy priority over departures for time slots. Thus departures are accommodated in slots left vacant by arrivals.

Error-free surveillance information is assumed. Navigation errors are assumed to be normally distributed random variables. The model can take into account: deviations from the nominal flight path, deviations from nominal aircraft velocities and descent angles, deviations in aircraft turn rates and final headings, and variations in pilot response times to controller commands.

7. Status of the Model: The model is operational. An ATC scenario for the New York City terminal area has been simulated for model validation purposes.

8. Quality of Documentation: The documentation is good. A flowchart of the simulation is included. Subroutine functions are individually described and the program variables are defined. A user's guide and a programmer's guide exist (attached to the report). No program listing is provided.

9. Extent of Model Validation: The results from the run on the NYC terminal area scenario were compared to data from CATER print-outs and flight strips. The comparison was almost impossible due to lack of pertinent data (arrival times at feeder fixes, flight path followed in the terminal area, etc.). Only the order of assignments to the runways and the aircraft landing times could be compared. When traffic density was heavy, giving arrivals priority effectively prevented any departures from being scheduled at some runways.

10. Modularity and Flexibility: The model can be easily adjusted with respect to the number of runways and entry fixes that it simulates. Changes in the control logic would require major model modifications.

11. Evaluation: This model has many features in common with Models A4.1 and A4.3. The assumption of error-free surveillance and the model's failure to account for wind effects are serious shortcomings. The sequencing and scheduling logic should be modified to allow scheduling of departures during periods of high arrival rates (see item 9 above). The model has not been tested at high operation rates where considerable holding occurs. A CRT display of the traffic should be incorporated for debugging and monitoring purposes.

In general, this model appears to be at an earlier stage of development and less realistic and flexible than Model A4.1. The lack of a flexible control logic (see item 6 above) is the model's most important deficiency.



### MODEL A4.3

1. Primary Model Category: Models of Terminal Airspace

2. Reports Used to Evaluate the Model:

i) Title: Stochastic Simulation of Terminal Area Airspace

Author: Val M. Heinz

Agency: Flight Transportation Laboratory, MIT

Report #: MIT, M.S. Thesis, 115 pages

Date: September 1976

ii) Title: Stochastic Simulation of Terminal Area Airspace,  
User's Manual

Author: Val M. Heinz

Agency: Flight Transportation Laboratory, MIT

Report #: Unpublished

Date: September 1976

3. Author's Abstract: A computer simulation has been developed to aid in the testing of various Air Traffic Control (ATC) strategies. Written in Fortran, the simulation can model an arbitrarily large segment of airspace, including multiple airports, and can handle any number of types of aircraft. Users need only supply environment-specific information, such as the location and type of navigational aids, and the desired aircraft mix.

The effects of dominant functional error sources have been included, as have dynamic response characteristics in the high frequency (less than 30 seconds response time) range. Composite design and structured programming techniques have been incorporated throughout the simulation to facilitate maintenance and modification of the software.

4. Model Description:

4.1 Model Type: Simulation; probabilistic

4.2 Factors of National Airspace System Related to the Model:

This model is sensitive to Air Traffic Control rules and procedures, pilot and aircraft responses, errors in the navigational, surveil-

lance and air data systems, and the wind environment. It can be used to evaluate alternative ATC terminal area procedures and strategies.

4.3 Input Data Requirements: Aircraft mix; terminal area geography (location and type of navigational and surveillance aids, runway orientation, location of entry fixes, etc); weather conditions (prevailing wind distribution); a set of commands for each aircraft in the system. The latter is required since, at present, controller activity is not simulated by the model.

4.4 Outputs Obtainable: A wide variety of outputs are readily obtainable at a very disaggregate level (for example delay experienced by each aircraft, number of commands given to each pilot, total time in the system for each aircraft, etc.). The user is required to prepare a computer program which will perform the statistical analysis of the specific outputs of interest for the specific application at hand.

5. Computer-Related Characteristics: The computer program is written in FORTRAN (WATFIV or G1 compiler). Test runs involving only one or two aircraft at a time are reported. The program is estimated to cost \$2 to \$3 per simulated aircraft-hour.

6. Major Assumptions: The errors in the ATC system are assumed to be normally distributed with zero mean. The aircraft dynamic response is represented by detailed mathematical models. The pilot is assumed to monitor continuously all of the (noisy) readings of the available navigational aids. This assumption is correct in the case of an autopilot. It is, however, over-optimistic in the case of a human pilot who intermittently checks his instruments. It is assumed that the pilot does not respond to small deviations from the commanded state. Pilot response to larger deviations is assumed to be a linear function of the deviation, with a specified maximum value for very large deviations.

7. Status of the Model: The computer program is actively maintained and updated. It will be used to evaluate an automated terminal area ground control strategy currently under development

at MIT.

8. Quality of Documentation: Documentation of the model is excellent. The model description is intended for the researcher who is interested in understanding the model's logic and structure, its mathematical background, and its applicability. The computer program is very clearly documented in the User's Guide which supplements the report (see reference ii above).

9. Extent of Model Validation: The model has not been validated against field data. After extensive testing, the simulation of aircraft dynamic response has proven satisfactory.

10. Modularity and Flexibility: The model can be easily modified and expanded. It can also be easily interfaced with a human or computerized controller to evaluate alternative ATC strategies.

11. Evaluation: This model differs from other terminal airspace simulations in its detailed modeling of aircraft dynamic response, and of error sources in ATC system functions. This is an important feature since, in the tightly controlled airspace around major airports, these NAS factors may easily dominate in determining aircraft position and thus significantly affect the level of safety provided by a given ATC system. The model can therefore be very useful in evaluating advanced ATC systems, especially when precision delivery of aircraft at waypoints is required (e.g., use of 4-D navigation techniques, etc.).

In general, this model represents an ambitious undertaking which is still at an early stage of development. The lack of a program that simulates ATC surveillance and control logic is the model's principal deficiency at this time.



MODEL A4.4

1. Primary Model Category: Models of Terminal Airspace

2. Reports Used to Evaluate the Model:

i) Title: GASP Simulation of Terminal Air Traffic System

Authors: Jason C. Yu, Wilber E. Wilhelm, Jr. and  
Samuel A. Akhand

Agency: NASA, Langley Research Center

Report #: Journal of Transportation Engineering, (ASCE),  
Vol. 100, No. TE3, pp. 593-609

Date: August 1974

ii) Title: Discrete Event Simulation Model of Terminal Air  
Traffic Control System

Authors: J. C. Yu and S. A. Akhand

Agency: NASA, Langley Research Center

Report #: Traffic Control and Transportation Systems:  
Proceedings of the Second Symposium, Monte  
Carlo, Monaco, pp. 601-602

Date: September 16-21, 1974

3. Author's Abstract: A somewhat simplified fast-time simulation model of the air terminal system was developed. This model proved the flexibility and capability of a somewhat unique modeling philosophy to simulate the air terminal system. A discrete events-type of simulation model was used. An event is defined as an occurrence which may alter the state of the system. The GASP simulation language was used as an executive controller of the simulation. The GASP provides an efficient and proven means of simulating large-scale systems. Since the discrete events simulation concept suitably offers the capability of evaluating the air-terminal system in a speedy and economical fashion, this research employed the essence of this philosophy but greatly extended the number of system components included and the ease of applying the model to an actual situation. The model considered the effects of pertinent facets of the actual system, yet was flexible enough to be easily applied to any particular air-

terminal center using present or future component equipment and procedures.

#### 4. Model Description:

4.1 Model Type: Simulation; probabilistic

4.2 Factors of National Airspace System Related to the Model:

The model relates ATC rules and procedures, aircraft performance, safety requirements, and runway capacity to aircraft delays and ATC system performance in the terminal airspace.

4.3 Input Data Requirements: Aircraft mix; airways geometry; airport runway layout; interaction among multiple runways; traffic levels; required minimum separations; and wave-off probabilities.

4.4 Outputs Obtainable:

a) Simulation Summary

This includes: the mean, standard deviation, minimum and maximum time the aircraft spent in each of the terminal area sectors; average delay of aircraft in each sector; total number of aircraft in the system by hour of day and aircraft type; total number of landings; total number of takeoffs; number of communications between controller and pilot; total runway idle time; time-between-touchdowns.

b) Detailed Output

This consists of the relevant attributes of each "event" (e.g., a landing, a takeoff, a communication, etc.) which took place during the simulation period (e.g., type of event, time the event occurred, identification of aircraft involved in this event, etc.).

5. Computer-Related Characteristics: The computer program is written in GASP, a FORTRAN-based, general purpose simulation language. No information on the cost of runs is reported.

6. Major Assumptions: Aircraft dynamic response is not simulated in detail. The flight from the entry fix to touchdown consists of 5 stages (holding, approach, merging, final approach

and touchdown). Aircraft are considered only at instances when a change of their flight stage occurs. The controller is assumed to do what is necessary to assure safe separation while aircraft are in the approach and merging stages. One of two sequencing schemes may be used: (a) First-come, first-served and (b) speed class sequencing. No explanation of how the latter can be accomplished is given.

7. Status of the Model: The computer program is operational and has been tested for internal verification. Eight experimental runs were conducted and in each case the results were as anticipated. These runs are not documented.

8. Quality of Documentation: In the references cited the model is not described in great detail. The flowcharts which are included present the basics of the model's logic very well. No program listings are included. No User's Manual is reported.

9. Extent of Model Validation: The model has been validated against data from the Atlanta airport. The simulation results are not documented in the report but they are said to compare well with the field data.

10. Modularity and Flexibility: Slight modifications in the model's logic require little effort, especially in view of the use of GASP. More extensive modifications of the model to include sensitivity to wind effects, human factors, flight dynamics of aircraft, etc., would require considerable reprogramming and remodeling.

11. Evaluation: This model is a macroscopic one, sacrificing detail for the sake of "ease-of-use." Unlike Models A4.1, A4.2 and A4.3, it does not simulate in detail the movement of aircraft through the terminal area and, therefore, it is not an appropriate model for investigating such issues as approach control strategies and flight path merging strategies. On the other hand, the model's simplicity and the limited effort required for the collection of input data make it suitable for other types of studies such as a preliminary evaluation of an ATC system in a terminal area with a large number of airports. Use of the model is recommended but



interpretation of the results should be done with care, recognizing the model's limitations.

## MODEL A4.5

1. Primary Model Category: Models of Terminal Airspace
2. Report Used to Evaluate the Model:

Title: User Delay Cost Model and Facilities Maintenance Cost Model for a Terminal Control Area, Volumes I and II: Model Formulation and Demonstration, User's Manual and Program Documentation

Author: L. B. Greene, J. Witt, and M. Sternberg-Powidzki

Agency: ARINC Research Corporation

Report #: AAF-220-78-01

Date: May 1978

Other I.D.: Contract No. DOT-TSC-1173-3

3. Author's Abstract: The User Delay Cost Model (UDCM) is a Monte Carlo computer simulation of essential aspects of Terminal Control Area (TCA) air traffic movements that would be affected by facility outages. The model can also evaluate delay effects due to other factors, such as weather, aircraft schedule intensity and approach minima. Although the Boston TCA was selected as the study vehicle for development and demonstration, the model is structured so it can be applied to other TCA's.

### 4. Model Description:

4.1 Model Type: Simulation; probabilistic

4.2 Factors of National Airspace System Related to the Model: The model incorporates current Air Traffic Control rules, is sensitive to the operational status of various navigational and surveillance equipments, weather conditions and traffic levels, and produces estimates of delay in a TCA.

4.3 Input Data Requirements: Weather data; arrival rate (as a function of weather, destination airport, time of day); distribution of aircraft types (as a function of weather, and destination); terminal area geometry (runway orientation, distances from entry fixes to each runway, etc.); facilities necessary for each approach at each runway; minima for each approach serving each runway; mean-times-between-failures (MTBF) and mean-time-to-restore (MTTR)

for each facility; minimum required separations at the runway threshold.

4.4 Outputs Obtainable: Various delay statistics for a given traffic level and maintenance policy. These are gathered separately for each type of aircraft and include: total delay accumulated by landings and takeoffs; percent of landings and percent of takeoffs delayed; percent of landings diverted to their alternate destinations.

5. Computer-Related Characteristics: The computer code is written in GPSS. It is operational and requires approximately 280 K bytes of memory. No information is provided on typical running times.

6. Major Assumptions: The Terminal Control Area is modeled in a very simplified manner. The controller's acceptance rate (which depends on the operational status of the navigational equipment) determines the rate at which aircraft are released from the holding stacks. The first-in, first-out discipline based on the time of system entry is used to determine the next aircraft to leave the holding stack. Prior to leaving the holding stack the aircraft's ETA is computed based on a prespecified nominal distance between the holding stack and the runway threshold. Each aircraft is sequenced to land in the first available landing slot (i.e., so that the already existing schedule of movements is not disturbed at all). Each aircraft absorbs all the required delay at the holding stack. The controller is assumed to maintain the required separations between aircraft at all times during their approach to the runway.

The procedure by which each landing is assigned to a runway is very detailed and representative of actual ATC procedures. The runway assignment depends on wind speed and direction, types of approach available, weather conditions, and the facilities' operational status.

Some other important assumptions are:

- a) Takeoffs are handed-off to the En Route Control Center,



thus disappearing from the model immediately after they leave the runway.

b) Secondary operations (i.e., landings directed to other airports in the area, etc.) are essentially neglected.

c) The schedule, once determined, never changes and is assumed to be followed exactly. Thus, the possibility of missed approaches or of failure of an aircraft to follow the schedule is neglected.

d) Deterioration of voice radio communications is not modeled.

7. Status of the Model: The model is operational and has been used to predict delays experienced at Logan International Airport in Boston.

8. Quality of Documentation: The documentation is very good. A user's manual has been prepared and includes many flow charts detailing the model's logic as well as the program listings and the data used for the Boston study.

9. Extent of Model Validation: Ten runs of the model were conducted and documented in this report. They show that the model functions correctly and exhibits the expected sensitivity to weather conditions, aircraft arrival rate, and facility availability. No attempt was made to validate the model against actual field data.

10. Modularity and Flexibility: Few changes are required in order to adapt the model to a specific terminal area. The data required to run the model may be difficult to collect (in particular, weather-related data). The computer code is not modular, and thus modifications of the logic might present substantial problems.

11. Evaluation: The model was developed for use in conjunction with other models to determine the effectiveness of various facility maintenance policies. This, to a great extent, justifies the simplifications introduced in the modeling. The model logic

has good theoretical foundations namely that:

a) the capacity of an airport depends on the achievable time intervals between successive operations.

b) the delay experienced depends primarily on the airport's capacity, the traffic levels, and the time-of-day variations in traffic levels.

c) equipment outages affect airport capacity by increasing the time intervals between successive operations as well as the required separations during the approach phase.

d) weather conditions have a major effect on required separations and have to be included in the model.

Several refinements, however, could be made without greatly compromising the speed of execution. In particular:

a) the possibility of missed approaches should not be neglected.

b) the computation of the controller's rate of acceptance of aircraft should be improved.

c) the sequence and schedule of movements should be allowed to change under certain circumstances.

d) the assumptions that all aircraft absorb all the delay at the holding stacks is severe, rather unrealistic, and may significantly influence the delay estimates.

As a final comment, we note that although the model may be used to compute delay effects due to factors other than facility outages (for example, aircraft schedule intensity and approach minima) other models in categories A2 and A3 (such as Models A2.2, A2.4, A3.1 and A3.2) would be much better suited for this purpose.

#### MODEL A4.6

1. Primary Model Category: Models of Terminal Airspace

2. Report Used to Evaluate the Model:

Title: An Optimal Control Approach to Terminal Area Air  
Traffic Control

Author: D. K. Schmidt and R. L. Swain

Agency: Purdue University

Report #: Journal of Aircraft, Volume 10, #3, pp. 181-188

Date: March 1973

3. Author's Abstract: In this investigation the problem addressed is the specification of the curved approach paths and landing sequence for a group of aircraft desiring to land in a terminal area such that the terminal-area system performance is maximized. The multiple-aircraft problem includes the aspect of competition or cooperation between the vehicles by formulating the problem as a set of disconnected optimal trajectories. The flight paths are governed by kinematic equations of motion while in flight and terminal-time separation inequality constraints between trajectories are imposed. The performance criterion for the system is the sum of the flight durations plus the integrated weighted accelerations of the aircraft. The solution approach employs penalty functions for the treatment of the inequality constraints and is based on the steepest descent algorithm. A number of examples are presented which involve interaction between two and three aircraft. Parametric results are also included for some single aircraft examples. The basic approach assumes the initial conditions are known for all the aircraft before the solution process begins. In addition, a sequential solution algorithm is also demonstrated which allows the initial conditions to be made known to the system only a short time before arrival into the terminal area. A comparison between the two algorithms is presented.

4. Model Description:

4.1 Model Type: Analytical; deterministic



4.2 Factors of National Airspace System Related to the Model: The model is sensitive to ATC separation standards, aircraft mix, aircraft performance and traffic levels.

4.3 Input Data Requirements: Aircraft mix; aircraft performance characteristics (landing speed, etc.); aircraft state upon entering the terminal area; separation standards; difficulty factors (weights) for the longitudinal, lateral, and vertical acceleration for aircraft of all classes (see item 3 above.)

4.4 Outputs Obtainable: Conflict-free 4-dimensional (4-D) paths for all aircraft in the system. The algorithm optimizes the system performance criterion (see Item 3 above). The optimum sequence of operations may be different from the first-come, first-served order.

5. Computer-Related Characteristics: The program runs on a CDC 6500 computer. Reported running times are: 40 seconds for computation of a single aircraft trajectory (unconstrained case), and 265 seconds for a three-aircraft example. No information as to a user's manual is given.

6. Major Assumptions: Aircraft of various flight characteristics (CTOL, STOL, Jets) are assumed to operate in the terminal area. The kinematic equations of motion are assumed sufficient to describe the aircraft movements. The aircraft are also assumed to have adequate navigational capabilities so they can follow precise 4-D paths (RNAV, MLS, etc.). The weights imposed on the aircraft accelerations are sufficient to avoid 4-D paths which do not conform to the aircraft's performance characteristics.

7. Status of the Model: The model is operational. Examples of runs and some results are given in this paper. No information on the model's availability is given.

8. Quality of Documentation: The paper is well written and explains the basic ideas and mathematical foundation of the model very well. References for more detailed explanations of the model are given. Several examples illustrate the model's capabilities and deficiencies.

9. Extent of Model Validation: Not applicable, since the model analyzes a new concept and field data do not exist.

10. Modularity and Flexibility: The model accepts aircraft of any speed class. Any initial or final conditions can be incorporated. Additional constraints, however, such as imposing an upper limit on the amount of delay that each aircraft type can be forced to suffer, would be difficult to incorporate.

11. Evaluation: This model is representative of a significant number of attempts to model the air traffic control process in the terminal area using concepts from the theory of optimal control. It is one of the most realistic optimization-oriented models in this area since it allows complete freedom in the path geometry, and aircraft of various speed categories. Furthermore, it is the only optimization model which combines sequencing decisions with optimal path determination. Unfortunately, the model requires too much computational effort to be realistically considered for implementation with a real-time automated terminal area control system at this time. Its contribution, therefore, is mostly theoretical for the time being.

#### MODEL A4.7

1. Primary Model Category: Models of Terminal Airspace
2. Report Used to Evaluate the Model:

Title: An Analytic Study of Near Terminal Area Optimal Sequencing and Flow Control Techniques.

Author: S. K. Parker, T. A. Straeter, and J. E. Hogge

Agency: NASA, Langley Research Center

Report #: AGARD-CP-105, Paper #12

Date: June 1973

3. Author's Abstract: This paper discusses optimal flow control and sequencing in the near terminal area. For simplicity, we consider a one-runway configuration with landings only, although many of the concepts involved may be extended to multiple runway configurations with both landings and takeoffs. To be more specific, we first propose a mathematical model of this simplified near terminal area which can be used to study various optimal sequencing and flow control concepts. Second, we indicate how the disciplines of optimal control theory, linear/nonlinear programming, and error analysis techniques can be used to analyze this model. Finally, we analyze the sequencing and flow strategies involved in a one-runway configuration with several classes of aircraft and time-to-turn-like approach trajectories. The near terminal area model is based upon two key assumptions. Namely, it is assumed that aircraft enter the near terminal area along previously determined (i.e. structured) approach paths. Moreover, it is assumed that the aircraft are segregated according to near terminal area performance capabilities. As we show, these assumptions provide a major computational advantage, that is, they enable one to decompose the sequencing and control problem into several much more tractable (and largely independent) subproblems.

In order to illustrate the previously mentioned ideas more clearly, a one-runway, two-approach path configuration is analyzed in detail. The trajectories are parameterized (and optimized) using a time-to-turn-like path with a harp delay pattern.



4. Model Description:

4.1 Model Type: analytical; deterministic

4.2 Factors of National Airspace System Related to the Model: The model relates terminal area ATC rules and procedures, aircraft performance characteristics, and aircraft sequencing strategies to runway capacity and delays.

4.3 Input Data Requirements: Aircraft mix, nominal approach path geometry, runway configuration, traffic levels, required minimum separations, and system performance criterion to be optimized.

4.4 Outputs Obtainable: a) Optimized delay paths geometry, b) Optimal ground-control decisions vis-a-vis aircraft sequencing at any point in time.

5. Computer-Related Characteristics: No computer related characteristics are reported in this paper, although results of computer-aided optimizations are discussed. Moderate programming effort is required to implement major parts of the model.

6. Major Assumptions: There are three major assumptions in the models presented. First, aircraft enter the terminal area along predetermined (structured) approach paths. Second, the aircraft are segregated according to their near terminal area capabilities. This means that each entry fix has a specific aircraft class associated with it and only aircraft of this class enter the terminal area from this entry fix. Third, it is assumed that the number of aircraft in conflict at the merging gate (outer marker) will be small. This assumption is crucial since the optimal merging order is determined by enumeration of all possible merging orders.

7. Status of the Model: No information is provided as to the status of the computer programs.

8. Quality of Documentation: The various mathematical models presented are described in detail and clearly. The detailed example presented is confusing primarily because the data are not representative of a real situation (e.g., landing speeds of 165 knots, outer marker at 2 nautical miles from the runway threshold).

9. Extent of Model Validation: Not applicable, since the model does not analyze an existing situation.
10. Modularity and Flexibility: The analysis is based on the assumption that the ATC process can be divided into independent subsystems. A collection of simple analytical models is used, each applicable to a different part of the ATC process. Each of these models can exist alone, and can be used independently of the others. The flexibility of the models, on the other hand, is limited and only minor variations (such as slightly different geometries of the approach paths) can be accommodated.
11. Evaluation: This paper addresses various optimization problems which are typically encountered in the analysis of ATC systems in the near terminal area, such as optimal path generation, optimal delay maneuvers, conflict resolution at the merging gate (outer marker), and sequencing of operations. Mathematical formulations are provided for the simplest instances of the problems addressed so the solutions should, at best, be considered of qualitative value only. The assumption of segregated traffic is rather severe, and in many ways avoids one of the most difficult issues in the analysis of ATC systems. Specifically the main shortcomings are:
- a) In generating approach paths, the relationship between fuel consumption and altitude is ignored, and the assumption that constant controls (deceleration, descent rate) are applied during each flight leg is unnatural and is bound to produce unacceptable paths from the pilot's workload viewpoint. The same comments apply to the determination of the optimal delay maneuvers.
  - b) In the sequencing problem the important issue is again avoided by assuming that only a small number of aircraft will be in conflict, and thus all possible aircraft sequences can be enumerated. This is true only when the traffic is light, in which case sequencing of operations is of little value.

In summary, the model reviewed here can be described as a fine and well-presented research effort which, however, is of limited practical applicability. It offers a good starting point for further research.

## MODEL A4.8

1. Primary Model Category: Models of Terminal Airspace

2. Reports Used to Evaluate the Model:

i) Title: Automated Aircraft Scheduling Methods in the Near Terminal Area

Author: L. Tobias

Agency: NASA, Ames Research Center

Report #: Journal of Aircraft, Vol. 9, No. 8, pp. 520-524

Date: August 1972

ii) Title: Optimum Horizontal Guidance Techniques for Aircraft

Author: H. Erzberger and H. Q. Lee

Agency: NASA, Ames Research Center

Report #: Journal of Aircraft, Vol. 8, No. 2, pp. 95-101

Date: February 1971

iii) Title: Terminal Area Guidance Algorithm for Automated Air Traffic Control

Agency: NASA, Ames Research Center

Author: Erzberger, H. and Lee, H.Q.

Report #: TND6773

Date: February 1972

3. Author's Abstract: A general scheduling algorithm for aircraft from terminal area entry to touchdown is developed. The method has the following novel features: 1) Many speed classes of aircraft are considered and speed variations within classes and along portions of the flight path are permitted. 2) Multiple paths are considered which may merge or diverge. The analysis is not restricted to one runway nor to landings only. 3) Landings are scheduled along conflict free paths in minimum time. The algorithm is currently being incorporated in a fast-time simulation of a STOL air traffic system.

4. Model Description:

4.1 Model Type: Analytical; deterministic



4.2 Factors of National Airspace System Related to the Model: ATC rules and procedures, safety requirements, air navigation, metering, spacing, and scheduling of aircraft operations.

4.3 Input Data Requirements: Aircraft characteristics and mix; terminal area geography (runway orientation, entry fixes, intermediate waypoints); minimum separation standards.

4.4 Outputs Obtainable: Conflict free paths which minimize the time-to-touchdown for each aircraft in the system.

5. Computer Related Characteristics: The computer code exists and is currently being incorporated in a fast-time simulation of a STOL traffic system. No further information is provided.

6. Major Assumptions: The terminal area is modeled as a set of nodes of 3 types: source nodes (entry fixes), sink nodes (outer marker) and intermediate nodes. As aircraft enter the terminal area they are spaced by the en route center so that no conflicts exist at the source nodes. The aircraft are assumed to adhere to the specified scheduled arrival time at each node. This may require holding and/or path stretching. The details of determining the flight path between nodes are presented in references (ii) and (iii) under item 2. Each aircraft is treated separately and its time-to-touchdown is minimized. The effect of other traffic is taken into account only in determining the conflict-free time "windows" for each node in the terminal area. Thus, once the schedule of an incoming aircraft is determined, it never changes as new traffic enters the system. Random effects such as wind and instrumentation errors are accounted for by using conservative values for the required separations.

7. Status of the Model: The model has been used to illustrate the effect of different speed classes of aircraft on airport capacity. Its usefulness is now being further tested in conjunction with an ongoing study at NASA/Ames Research Center.

8. Quality of Documentation: The mathematical formulation of the optimization problem and the solution method are clearly presented. Several simple examples are included. The computer code is not

documented in this paper. No information is given as to code availability or the existence of a user's manual.

9. Extent of Model Validation: The model outputs have not been compared with field data to evaluate the model's effectiveness as compared with current sequencing and spacing practices.
10. Modularity and Flexibility: Since no information is given on the computer code, its flexibility and modularity cannot be evaluated. The theoretical model is easily adaptable to various runway configurations and path structures. It can be interfaced with an ATC simulation for purposes of evaluation.
11. Evaluation: The model presented here is one of the best efforts to date in the area of automation of the controlling decisions in the near terminal area. Its major asset is its simplicity and its close adherence to current sequencing and spacing practices. It has, however, two key deficiencies which, in our opinion, will considerably reduce its effectiveness:

- 1) If aircraft are sequenced according to their speed class, a terminal constraint (the scheduled arrival time at the runway) will be imposed and some rescheduling will be required. The model cannot handle such constraints. In fact these requirements would seem to indicate the need to adopt a completely new methodology and approach.

- 2) The optimization criterion which is used is short-sighted and provides no assurance that the overall system will perform considerably better than it does under current practices. Using many alternative paths may alleviate this problem, but extensive changes in the model will be required to incorporate this modification.

### MODEL A5.1

1. Primary Model Category: Models of Air Route Traffic

2. Reports Used to Evaluate the Model:

- i) Title: A Mathematical Model for Predicting the Number of Potential Conflict Situations at Intersecting Air Routes

Author: W. Siddiquee

Agency: Stanford Research Institute, Menlo Park, California

Report #: Transportation Science, Vol. 7, No. 2, pp. 158-167

Date: May 1973

Other I.D.: None

- ii) Title: A Mathematical Model for Predicting the Duration of Potential Conflict Situations at Intersecting Air Routes

Author: W. Siddiquee

Agency: Stanford Research Institute, Menlo Park, California

Report #: Transportation Science, Vol. 8, No. 1, pp. 58-64

Date: February 1974

Other I.D.: None

3. Author's Abstract: (excerpted from references above)

A mathematical model is developed for predicting the expected number and duration of potential conflict situations at the intersection of air routes in the enroute environment. Given the intersection angle of two routes and the average flows and speeds of aircraft, the model predicts the average number of potential conflict situations per unit of time, the average duration of a potential conflict, and the total time the aircraft would spend in potential conflict if no preventive action were taken by controllers or pilots. A concept of intersection capacity based on conflict situations is introduced and a mathematical model of intersection capacity is developed. The models can be used in planning air route network geometry, as well as in providing guidelines for the establishment of suitable levels of traffic flow along various



routes.

4. Model Description:

4.1 Model Type: Analytical; deterministic

4.2 Factors of National Airspace System Related to the Model:

Relates air traffic characteristics and air route network configuration to number of conflicts (safety and workload indicator) at air route intersections, and to capacity of intersections.

4.3 Input Data Required: Average flow per hour of aircraft along each of the two intersecting routes; speed of aircraft along routes; angle of intersection of routes; longitudinal and lateral separation requirements of ATC; tolerable number of potential conflicts per hour.

4.4 Outputs Obtainable: Average number of conflicts per hour at the intersection; average potential conflict duration; total conflict time per hour at intersection; intersection capacity.

5. Computer-Related Characteristics: The relationships developed are all analytical and very simple to evaluate numerically. No need for a computer program exists.

6. Major Assumptions: Aircraft are assumed to fly at constant and standard altitudes; only violations of horizontal separation minima are considered; aircraft fly along the centerline of air routes; air routes are represented by straight lines; all aircraft flying at the same altitude are assumed to have the same speed; flow of aircraft along each route is assumed uniform (i.e., aircraft are equally spaced) with spacing at least as large as the longitudinal minimum separation requirement; aircraft approach and depart the intersection at the same heading; only two air routes intersect at each intersection.

7. Status of the Model: This model has been used with controller workload models developed by the Stanford Research Institute (see Part II, Section 6). The model is used to provide estimates of number and duration of conflicts at intersections. These estimates are, in turn, used by the workload models to compute controller workload.

8. Quality of Documentation: The mathematical analysis and the various assumptions are clearly and unambiguously presented.
9. Extent of Model Validation: No mention is made of any attempt to validate the model against actual field data.
10. Modularity and Flexibility: The model is a very simple one and can be applied wherever the various assumptions of the model hold true (at least approximately).
11. Evaluation: This model is based on a very simple geometrical analysis. The results that it provides are probably adequate whenever rough approximations are desired. A model developed subsequently by Dunlay (see Model A5.3) is based on less restrictive assumptions than the present model. For instance, in Model A5.3 more than two air routes are allowed to converge at an intersection. Aircraft on different air routes are also allowed to have different speeds and the flow of aircraft over each air route is not assumed to be uniform. Thus the Dunlay model, at the cost of developing slightly more complicated mathematical expressions, supersedes this model in terms of generality and accuracy.

## MODEL A5.2

1. Primary Model Category: Models of Air Route Traffic

2. Reports Used to Evaluate the Model:

i) Title: Computer-Aided Traffic/Airway/VOR(TAC) Network  
Methodologies, Vols. I and II

Author: W. Siddiquee

Agency: Stanford Research Institute, Menlo Park, California

Report #: FAA-RD-72-118, I and II

Date: August 1972

Other I.D.: Contract No. DOT-FA71WA-2547: AD-757805

ii) Title: Air Route Capacity Models

Author: W. Siddiquee

Agency: Stanford Research Institute, Menlo Park, California

Report #: Navigation, Vol. 20, No. 4, pp. 296-300

Date: Winter 1973-74

Other I.D.: None

3. Author's Abstract: Three simple air route capacity models are developed. The first model is based on the assumption of a common average speed of aircraft. This model gives a quick, rough estimate of the capacity of an air route. The second model is based on the assumption that overtaking of one aircraft by another is not allowed. This model gives the minimum capacity of a route. The third model is based on allowing for a certain maximum number of overtakings. This model gives a relatively more realistic estimate of the air route capacity. The models are intended as preliminary design aids for planners and designers of air route networks.

4. Model Description:

4.1 Model Type: Analytical; deterministic

4.2 Factors of National Airspace System Related to Model: Relates aircraft flow rates and cruising speeds, and ATC separation requirements to air route capacity.

4.3 Inputs Required: For the air route whose capacity is sought



the following data must be provided: length of the air route; cruising speeds for each aircraft type using the air route, and flow rates (in aircraft per hour) for each type; minimum longitudinal separation requirements for successive aircraft on the route; maximum permissible number (if any) of passings (=overtakes) per hour.

4.4 Outputs Obtainable: Capacity of the air route in terms of the number of aircraft traversing the route in an hour.

5. Computer-Related Characteristics: The models are analytical and are comprised of very simple mathematical expressions. A hand calculator (at most) is all that is required to obtain numerical estimates from these expressions.

6. Major Assumptions: The speeds of individual aircraft on air routes are assumed constant. It is assumed that aircraft do not deviate from their prescribed position along a route (such deviations might result in separations between aircraft being greater or less than the minimum standards). It is also assumed that a maximum number of aircraft passings allowed (per hour) can be obtained as an input to the models (probably by observing controller workload and behavior).

7. Status of the Model: These air route capacity models have been used in conjunction with the Relative Capacity Estimating Process (RECEP), also developed at SRI (see Model A6.4), to generate the frequencies of occurrence of overtake conflicts on air routes, thereby providing an estimate of controller workload and ATC sector capacity. The models have also been incorporated in a computer program developed at SRI (see first of documents under item 2 above) that calculates various attributes of area navigation route networks.

8. Quality of Documentation: The description of the models, including the derivation of the various analytical expressions, is clear, with several simple numerical examples used for illustration.

9. Model Validation: Some field data are presented to support the validity of the most sophisticated of the models (the one that allows some limited aircraft passing). The data are few and the

model cannot be considered validated.

10. Modularity and Flexibility: The models are very simple and can be easily adapted to various sets of circumstances, as long as the basic scenarios on which the models are built hold true.
11. Evaluation: The conceptual situations analyzed by these models are very simple. The capacity estimates provided by the models should be adequate for these situations. However, there are two disconcerting aspects of the analytical expressions obtained. First, the expression for air route capacity derived for the model that allows some aircraft passing (which also is, supposedly, the most realistic of the models) is independent of the minimum separation standard between aircraft. Thus the user must make sure to provide inputs that do not violate these standards, otherwise the model will yield unrealistic results. Second, all three models could be improved substantially by the simple inclusion of the probabilities of passage of different aircraft types. The models assume these probabilities to be known anyway, since the flow rates of all the aircraft types are required inputs to the models.

MODEL A5.3

1. Primary Model Category: Models of Air Route Traffic

2. Reports Used to Evaluate the Model:

- i) Title: Models for Estimating the Number of Conflicts  
Perceived by Air Traffic Controllers  
Authors: William J. Dunlay, Robert Horonjeff, Adib Kanafani  
Agency: Institute of Transportation and Traffic Engineering,  
University of California, Berkeley, California  
Report #: Special Report  
Date: December 1973  
Other I.D.: Contract No. DOT-FA-72-WA-2827; AD number:  
A023533
- ii) Title: Applications of Human Factors Data to Estimating  
Air Traffic Control Conflicts  
Authors: William J. Dunlay, Jr. and Robert Horonjeff  
Agency: Institute of Transportation and Traffic Engineering,  
University of California, Berkeley, California  
Report #: Transportation Research, Vol. 8, No. 3, pp.  
205-217  
Date: August 1974  
Other I.D.: Contract No. DOT-FA-72-WA-2827
- iii) Title: Analytical Models of Perceived Air Traffic Control  
Conflicts  
Author: William J. Dunlay  
Agency: Institute of Transportation and Traffic Engineering,  
University of California, Berkeley, California  
Report #: Transportation Science, Volume 9, No. 2, pp.  
149-164  
Date: May 1975  
Other I.D.: Contract No. DOT-FA-72-WA-2827
- iv) Title: On the Conflict Frequency at Air Route Intersections  
Author: David K. Schmidt  
Agency: School of Aeronautics and Astronautics, Purdue



University, West Lafayette, Indiana 47907

Report #: Transportation Research, Vol. 11, No. 3, pp. 351-355

Date: August 1977

3. Reviewer's Summary: A model of en route traffic leads to mathematical expressions for the expected number of crossing conflicts and overtake conflicts per unit time, as perceived by air traffic controllers. The number of conflicts depends on route geometry, separation criteria, aircraft velocities, aircraft flow rates on the air routes, and controller perception considerations. The model shows that the expected number of conflicts increases as the square of the aircraft flow rate. The fourth of the reports listed above extends the results of the crossing conflicts model by developing an expression for the variance of the number of conflicts. It is shown that the variance is large and this explains, in part, the appreciable variability in air traffic controller workload.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates traffic mix and characteristics, separation requirements, and controller characteristics to collision probabilities and, ultimately, to ATC system capacity and safety.

4.3 Input Data Requirements: En route minimum separation standards, traffic mix and travel speeds, geometry of air routes (including angles between pairs of air routes at intersections) and quantified information on how air traffic controllers perceive conflicts. The last item may be very difficult to provide, although the first of the reports quoted above suggests typical values for the information sought.

4.4 Outputs Obtainable: Expected values of the number of crossing conflicts and overtake conflicts per unit of time, as perceived by the air traffic controller. Variance of the number of crossing conflicts (in Schmidt report). From these quantities the capacity of air routes and of air route intersections can be computed as in Models A5.1 and A5.2.

5. Computer-Related Characteristics: No computer programs are discussed in the reports. The mathematical expressions developed are sufficiently simple to evaluate with any good pocket calculator.

6. Major Assumptions: Traffic flow on air routes is represented as a Poisson process. That is, the instant at which aircraft cross a specific point on an air route are random in time (i.e., they are samples from a Poisson process). This assumption is said to be supported by available field data.

The model also draws on the work of Dunlay and Horonjeff (see the second reference under item 2) on controller conflict perceptions for an expression for the minimum conflict distance for the case of crossing conflicts. However, any other suitable expression can be used to represent this distance in the model.

7. Status of Model: No information is provided in any of the reports as to whether this model has been used, or will be used, in connection with assessments of air route capacity.

8. Quality of Documentation: The logic of the model and the mathematical derivation of the various expressions are well presented. The second and third reports referenced in item 2 are particularly readable.

9. Extent of Model Validation: No information is presented on model validation other than data related to the Poisson assumption for traffic flow on air routes.

10. Modularity and Flexibility: The model leads to easily usable, closed-form analytical expressions which, in turn, can be used as inputs to other models concerned with overall ATC system capacity (see category A7) or with controller workload (see category A6).

11. Evaluation: This fine model leads to simple expressions which should provide good first-order approximations of the expected number of crossing and overtake conflicts. These estimates can, in turn, be used exactly in the same way as in the Siddiquee models (see Models A5.1 and A5.2) to obtain air route and air route intersection capacities. Since Model A5.3 is developed under more general assumptions than Models A5.1 and A5.2, it can be viewed as

superseding these models. The crossing conflicts model is very sensitive to assumptions as to how controllers perceive such conflicts and the numerical results are sensitive to the value of the minimum conflict distance used by controllers. The model also includes some major simplifications: for instance, with respect to crossing conflicts the analysis does not consider the fact that, in dense traffic, aircraft on any given air route arrive at any particular point on the route at regular intervals (due to minimum spacing) rather than randomly.

Use of this model to obtain estimates of numbers of conflicts is recommended, after the limitations of the model are properly understood. It should also be borne in mind that the model has yet to be validated against field data.



#### MODEL A5.4

1. Primary Model Category: Models of Air Route Traffic (ATC Communications)

2. Report Used to Evaluate the Model:

Title: A Nested Queue Model for the Analysis of Air Traffic Control Sectors.

Author: J. A. Modi

Agency: Research Triangle Institute, Research Triangle Park, NC.

Report #: Transportation Research, Vol. 8, pp. 219-224

Date: August 1974

Other I.D.: None

3. Reviewer's Summary: A "nested queue" model is developed for the purpose of aiding sector design and planning. A nested queue system is defined as "a system of multiple queues such that the service demand in one queue is created by some subset of the units (customers) of another queue."

In the case of this model, each sector is viewed as a service facility with  $s$  parallel servers, where  $s$  is the capacity of the sector (i.e., the number of aircraft that can move through the sector simultaneously). Aircraft enter the sector as long as there are less than  $s$  aircraft in it already, otherwise, a waiting line (in a holding stack) forms outside the sector.

The active aircraft in the sector ( $s$  or less) generate radio messages to the controller who is thus modeled as the "nested" system, i.e., the radio messages and the controller constitute a second queueing system, nested in the sector.

An extension of the model accepts a total of  $H$  aircraft holding within a sector, in addition to the  $s$  which are moving through the sector. The holding aircraft generate additional messages which increase the burden on the radio message/controller subsystem.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to the Model: The model relates the frequency at which radio messages are generated by aircraft in a sector, and the number of aircraft in a sector, to communications delays and aircraft delays.

4.3 Inputs Required: The average arrival rate of aircraft at a sector; the average time aircraft spend in the sector; the rate at which aircraft generate radio messages while in the sector; the maximum number of aircraft that can be active (i.e., traversing the sector) simultaneously; the maximum allowable number of holding aircraft in the sector; the average time it takes a controller to "process" a radio message from an aircraft.

4.4 Outputs Obtainable: Estimates of: the probability that n messages are "queued up" for processing by the controller; the average queue lengths for messages and for aircraft seeking to enter a sector; and the average waiting time of messages and of aircraft (to enter the sector).

5. Computer-Related Characteristics: It is simple to write computer programs that would provide numerical estimates from the mathematical expressions derived in the model.

6. Major Assumptions: The arrival of aircraft at sectors, and the generation of messages from any given aircraft in a sector, are both assumed to be random, and are thus modeled as Poisson processes. The probability density functions for the time that aircraft spend in sectors, and for the processing time of radio messages, are assumed to be negative exponentials.

A "steady-state" (i.e., "long-term equilibrium") type of analysis is performed which assumes that arrival rates of aircraft, message generation, and processing rates, etc., all remain constant over time.

7. Status of the Model: No information is provided on whether this model has been used in any project related to ATC planning.

8. Quality of Documentation: The report is often vague and con-

fusing. In particular, the main equations of the model are presented without any explanation and are probably incomprehensible to all but experts in queueing theory. A few typographical errors in the equations compound the problem.

9. Model Validation: No attempt to validate the model with actual field data is mentioned in the report.

10. Modularity and Flexibility: The assumptions mentioned under item 6 are all crucial to the development of the queueing equations on which the model is based. Any changes in these assumptions would lead to analytically intractable queueing models. Thus the model is inflexible with respect to its major assumptions.

11. Evaluation: This model is a straightforward application of two classical queueing systems to the ATC area. In fact, its main problem is that "reality" has been stressed to fit the existing queueing theory results (rather than the other way around). This leads to the use of the very questionable assumption that all the variables in the model are described by negative exponential probability density functions.

The model is intended as a preliminary analysis tool, and it is conceivable that it can be useful under certain circumstances. However, the model's emphasis on queueing times for radio messages is misplaced, since long waiting times for ATC communications, of the magnitude shown in the numerical example that illustrates the model, will never be tolerated in other than extreme failure cases. Much more significant problems are those of sector capacity, and the controller's message processing capacity, both of which are regarded by the model as externally provided inputs.



MODEL A5.5

1. Primary Model Category: Models of Air Route Traffic (ATC Communications)
2. Reports Used to Evaluate the Model:
  - i) Title: Modeling Air Traffic Performance Measures,  
Vol. I: Message Element Analyses and Dictionaries,  
Vol. II: Initial Data Analyses and Simulations  
Author: J. S. Hunter, D. E. Blumenfeld and D. A. Hsu  
Agency: Princeton University, Princeton, New Jersey  
Report #: FAA-RD-73-147, I and II  
Date: July 1974  
Other I.D.: Contract No. DOT FA72NA-741
  - ii) Title: Simulation Model for New York Air Traffic Control Communications  
Authors: J. S. Hunter and D. A. Hsu  
Agency: Princeton University, Princeton, New Jersey  
Report #: FAA-RD-74-203  
Date: February 1975  
Other I.D.: Contract No. DOT FA72NA-741
  - iii) Title: Applications of the Simulation Model for Air Traffic Control Communications  
Authors: J. S. Hunter and D. A. Hsu  
Agency: Princeton University, Princeton, New Jersey  
Report #: FAA-RD-76-19  
Date: February 1977  
Other I.D.: Contract No. DOT FA72NA-741
  - iv) Title: Analysis of Simulation-Generated Responses Using Autoregressive Models  
Authors: D. A. Hsu and J. S. Hunter  
Agency: Princeton University, Princeton, New Jersey  
Report #: Management Science, Vol. 24, No. 2, pp. 181-190  
Date: October 1977  
Other I.D.: None

v) Title: Simulation Model for Air Traffic Control Communications

Author: Robert Mulholland

Agency: Federal Aviation Administration, National Aviation Facilities Experimental Center, Atlantic City, NJ

Report #: FAA-NA-76-30

Date: July 1977

3. Reviewer's Summary: The model reviewed here is a discrete-event (or "event-paced") simulation of aircraft/controller voice communications in ATC sectors. A completed conversation between an aircraft in a sector and the controller is termed a "communications transaction" (CT). Each CT is composed of separate "transmissions" (TR's) which are made alternately by pilot and controller. Finally, each TR contains one or more "message elements" (ME's).

The simulation represents the communications channel as a "facility". Access to the channel is controlled by a queue which operates in a "first-in, first-out" mode. During each CT, the channel is occupied exclusively by that CT for the required number of seconds. In addition, an interval of at least one second is imposed between the end of one CT and the start of another.

All active aircraft in the simulated sector "compete" for access to the channel and their CT's queue-up if the channel is busy. When an aircraft has completed its CT, a test is made to determine whether all of its required transactions have been completed. If not, the model generates an intercommunications gap until the next CT from this aircraft. After the clock has been advanced to the end of that gap, that next CT joins the queue for the communications channel. The same procedure is repeated until the last CT from each aircraft has been completed, at which time the aircraft leaves the sector and is removed from the system.

#### 4. Model Description:

4.1 Model Type: Simulation; probabilistic

4.2 Factors of the National Airspace System Related to the Model:

The model relates sector type and function as well as the number of

aircraft in a sector, to communications workload and, consequently, to controller workload and sector capacity.

4.3 Inputs Required: Probability distributions and related parameters (such as mean values, variances, etc.) are required for the following variables: aircraft interarrival times (to the sector); number of transactions (CT's) per aircraft; number of transmissions (TR's) per CT; TR lengths; intercommunication gap lengths.

4.4 Outputs Obtainable: Sector aircraft loading (instantaneous number of aircraft in sector, average number of aircraft, maximum number of aircraft); communications channel loading (channel utilization, number of transactions, length of transactions); channel queueing characteristics (waiting time for CT's, number of CT's in the queue, duration of channel busy periods).

5. Computer-Related Characteristics: The simulation is written in the GPSS V language that allows FORTRAN linkages to external mathematical functions and operations. The program has been run on a 360/91 IBM computer. No information is given on typical running times and storage requirements.

6. Major Assumptions: The probability distributions used in the model are based on analysis of data collected over a busy two-hour period at all 101 sectors of the New York ATC metroplex (ARTCC and terminal area control) on April 30, 1969.

The number of transactions (CT's) generated by two different aircraft in the same sector are assumed to be statistically independent of each other. However, the number of transactions is correlated to the intercommunication gap lengths.

No change in the frequency or length of CT's with increase in channel utilization and/or queue length is assumed. A first-come, first-served queue discipline is used for sequencing the access of CT's to the channel.

7. Status of the Model: The model has been used to explore the sensitivity of ATC channel utilization and of voice communications delays to various changes in the values of the parameters used as inputs to the model. It is not known whether the model is



currently being used in connection with any aspects of ATC planning.

8. Quality of Documentation: The documentation of the model is voluminous and of uniformly excellent quality. Coverage includes: data collection and statistical analysis; model logic; model validation; model extensions and applications. A listing of the computer program and a detailed example is presented in the second of the documents referenced in item 2 above (FAA-RD-74-203).

9. Model Validation: The model can be considered fully validated for the levels of utilization of ATC communications channels commonly encountered. The model was calibrated with, and validated against, data from the New York ATC area. The New York-calibrated model was subsequently used to perform simulations of the Houston ARTCC sector functions with some adjustments to account for local parameter values. The performance of the model in this new environment was very good.

10. Modularity and Flexibility: The model can be adapted to various types of sectors. A data base has been developed for en route sectors (high and low altitudes) as well as terminal area sectors.

11. Evaluation: This model represents a truly exemplary effort. It is based on a very large volume of collected data that have been analyzed in great detail; it is supported by a meticulous and highly sophisticated statistical validation of its outputs against field data; and its potential uses and applications have been clearly described and explored.

Some reservations are in order with regard to using the model, as is, to analyze situations with very high communications channel utilizations. Under such circumstances, one might reasonably expect that the characteristics of controller/pilot interactions might be different from what they were in the moderately congested communications environment from which the data (that were used in the simulation) were collected. For instance, one might expect CT's to be shorter or certain message elements (ME's) to be omitted when communications channels are very busy.

Considerably more work is needed if the single sector communi-

cations model is to be applied to groups of sectors, in the manner described by the second and third of the reports referenced in Item 2 above.

In general, however, this model is an excellent one and its use for analysis of communications workload and delay problems is strongly recommended. The data analysis and the validation tests that have been performed in connection with this model, set a standard unmatched by any other model that we have reviewed in this volume.

### MODEL A6.1

1. Primary Model Category: Controller Workload and Performance Models

2. Report Used to Evaluate the Model:

Title: Notes on the Measurement of Control Load and Sector Design in the Enroute Environment

Author: Bar Atid Arad

Agency: Federal Aviation Agency

Report #: Appendix, Final Report of Project 102-11, Systems Design Team

Date: June 1964

Other I.D.: NTIS # AD659035

3. Reviewer's Summary: This report creates a model of controller workload consisting of three parts: background, routine, and air-space. Background workload is ignored. Routine workload for a sector is directly proportional to the aircraft handled per hour. A routine work coefficient,  $K_1$ , is weighted for the normal kinds of operational events which occur in that sector. Airspace workload arises from potential conflicts between aircraft, and is proportional to the square of aircraft handled. An "equivalent volumetric flow organization factor,  $g_{eh}$ ," is used to establish the overall conflict rate as a function of traffic flow, and a conflict work coefficient  $k_2$ , is used to obtain the Airspace Load. The report, using these methods of estimating workload, discusses problems of designing an ATC sector.

4. Model Description:

- 4.1 Model Type: Analytical; deterministic

- 4.2 Factors of National Airspace System Related to the Model:

Traffic flow factors and sector geometry are used to determine controller workload.

- 4.3 Input Data Requirements: Traffic flow rates for the sector;



aircraft altitude distribution; aircraft speed distribution; work coefficients for routine events and conflicts; sector geometrics and area; aircraft separation standards.

4.4 Outputs Obtainable: Expected values for conflict rate in the sector; routine and airspace workload ratings as a function of traffic flow rate.

5. Computer-Related Characteristics: No computer program is known to exist.

6. Major Assumptions: This model assumes that the deterministic values of average traffic flow, airspeed and altitude distributions, etc., can be used to compute a steady-state average value for controller workload. It uses subjective assessments by controllers of relative workload coefficients for various kinds of control events to produce relative measures of workload. It assumes that overall traffic coefficients can be found for a sector, which are assumed to remain constant over time.

7. Status of Model: It does not seem that this method of assessing sector workload is still in use. This report proposes a validation study as the next step to confirm the model's usefulness.

8. Quality of Documentation: The notes are written for the layman controller who is expected to learn to use the model in validation studies. As a result, there are numerous examples of the calculations for each step in using the model.

9. Extent of Model Validation: The subsequent work by Jolitz (see Section 6.7, Part II) compares this method with other assessments of workload.

10. Modularity and Flexibility: The model can be used to predict conflict rates at airways intersections and overtake conflicts along on airway. However, later work by Siddiquee and Dunlay (see Models A5.1, A5.2, and A5.3) would appear to be more useful for these purposes.

11. Evaluation: The model provides a very pragmatic method for computing controller workload measures for a sector. However, it

requires much additional field work aimed at comparing its workload measures with controller subjective assessments of workload, and obtaining values for certain traffic coefficients and their day-to-day variability. This model seems to have provided a starting point for all subsequent work in modeling sector activities and controller workloads.

MODEL A6.2

1. Primary Model Category: Controller Workload and Performance Models

2. Report Used to Evaluate the Model:

Title: Automation Applications in an Advanced Air Traffic Management System, Vol. VA, Delta Simulation Model-User's Guide; Vol. VB, Delta Simulation Model - Programmer's Guide

Authors: F. Mertes, K. Willis, E. C. Barkley

Agency: TRW Systems Group, McLean, Virginia

Report #: DOT-TSC-OST-74-14, Vol. VA, VB

Date: August 1974

Other I.D.: PB-236809

3. Author's Abstract: The Advanced Air Traffic Management System (AATMS) program is a long-range investigation of new concepts and techniques for controlling air traffic and providing services to the growing number of commercial, military, and general aviation users of the national airspace. This study of the applications of automation was undertaken as part of the AATMS program. The purposes were to specify and describe the desirable extent of automation in AATMS, to estimate the requirements for man and machine resources associated with such a degree of automation, and to examine the prospective employment of humans and automata as air traffic management is converted from a labor-intensive to a machine-intensive activity.

Volume V describes the DELTA Simulation Model. It includes all documentation of the DELTA (Determine Effective Levels of Task Automation) computer simulation developed by TRW for use in the Automation Applications Study. Volume VA includes a user's manual, test case, and test case results. Volume VB includes a programmer's manual.

4. Model Description:

- 4.1 Model Type: Simulation; probabilistic



4.2 Factors of National Airspace System Related to Model: This model relates controller workload to sector geometry, demand for ATC services and aircraft performance characteristics.

4.3 Input Data Requirements: There is a very large set of input data described in extensive detail by the report. These data consist of: 1) a large set of variables and parameters which describes the probabilities of control events, duration limits for tasks, thresholds for control actions, maximum allowable navigation errors, etc.; 2) data describing the task durations and their allocations among control positions within a sector (or resource pool in the terminology of the report); 3) geometric data describing the sector size; 4) performance data for aircraft types, and desired miss distances; and 5) detailed data for the flight plans of all aircraft to be operated in the simulation.

4.4 Outputs Obtainable: There are two standard reports; a Raw Summary, and a Post Processor Report. The Raw Summary provides the percentage time each "element" (man or machine) of a "resource pool" (control position) is busy, on the average, over the period simulated by the run. The Post Processor Report summarizes the number of task occurrences, total and by "jurisdiction" (sector); and also, for each aircraft flight, provides a time history of the phases of flight and a summary of the task occurrences caused by it.

5. Computer-Related Characteristics: The model is implemented on a CDC 6600, and is written in Fortran IV. It consists of over 200 subroutines and has variable core requirements depending on the dynamic memory allocated. With an overlay procedure unique to CDC and TRW, the core size was 117000 octal words. To run the model on another computer, it appears that several software modifications are necessary. No information is provided on running times.

6. Major Assumptions: The model assumes that generic ATC control activities are defined by 17 main functions. These are broken down into sub-functions, and further into 165 tasks. These tasks are related to ATC events caused by aircraft flights. They are assigned to an element (man or machine) of the ATC system, with

time requirements (or instruction counts), and a priority over other tasks assigned to that element. The workload on an element is assumed to be measured by the percentage time the element is busy. It is assumed that the kinematics of aircraft motion are not important in determining these measures, so that aircraft motion is very simply modeled. It uses simple algorithms for metering and spacing, and also for conflict prediction, detection, and resolution.

7. Status of the Model: The operation of the model was demonstrated on a "verification" run based on operations in the San Francisco terminal area. It is not known if further test runs were performed, or if the model is currently available.

8. Quality of Documentation: There is both a User's Guide and a Programmer's Guide which contain a large amount of detailed data about the model, its operation and its coding. However, it is rather difficult to decipher and to evaluate its completeness since it is a very large computer model.

9. Extent of Model Validation: No description of any attempts to validate the model by comparing it with current ATC operations is provided in these reports.

10. Modularity and Flexibility: The model is a global model which is flexible in that it can simulate any portion of an ATC system under varying assumptions about the degree of automation. It is not modular since the complete model must be used.

11. Evaluation: This constructive simulation approach is necessary when considering future ATC system configurations which are quite different from today's system, but extensive validation testing is required to gain confidence in the results from model runs. The results of this model would be very sensitive to the assumptions about task definition, task times, and task assignments. As with all simulation models, the question arises as to statistical significance of the results of a model run, particularly when traffic levels approach capacity levels. The model is large and presumably expensive to run over long simulation periods. Given these

difficulties, it would be preferable to simulate a single sector rather than construct a model to represent entire en route and terminal areas.



### MODEL A6.3

1. Primary Model Category: Controller Workload and Performance Models

2. Report Used to Evaluate Model:

Title: On Modeling ATC Workload and Sector Capacity

Author: David K. Schmidt

Agency: Stanford Research Institute/Purdue University

Report #: Journal of Aircraft, Vol. 13, No. 7, pp. 531-537

Date: July 1976

3. Author's Abstract: This paper describes a semi-empirical, deterministic work load model and an evaluation procedure intended to aid in the design and evaluation of those units of airspace (sectors) under the jurisdiction of a team of air traffic controllers. The technique relates the traffic variables, route and sector geometry, and control procedures to an index that quantifies the workload required on the part of the air traffic control (ATC) team. Workload is considered to constitute the required sector evaluation criterion when maximum overall ATC facility capacity and manning efficiency are desired. With proper calibration, the model may be used to assess the impact on workload and sector capacity of future automation features. An example evaluation of an actual high altitude, en route sector is included.

4. Model Description:

4.1 Model Type: Analytical; deterministic

4.2 Factors of National Airspace System Related to Model: Relates aircraft characteristics, route and sector geometry, demand level, and control procedures to controller workload.

4.3 Input Data Requirements: Mix of aircraft speeds; airways route structure; traffic flow rate on airways; sector total traffic flow rate; traffic event rates; traffic event durations.

4.4 Outputs Obtainable: A measure of workload called CDI (Control Difficulty Index) for a given sector under given conditions; maximum

traffic flow rates for the sector.

5. Computer-Related Characteristics: No Computer code exists.

6. Major Assumptions: The basic premise of this model is that workload (or "control difficulty") is related "to the frequency of events which require decisions to be made and actions to be taken by the controller team, and the time required to accomplish the tasks associated with these events." These events are classified into three categories: routine procedural events; potential overtaking conflicts along air routes; and potential conflicts between aircraft at air route intersections. Thus the model essentially consists of estimating the frequency of each these types of events and then multiplying these frequencies by "weights" which indicate the relative degree of difficulty of each event. The weights are obtained "through the use of direct measurement, video tape recording, and structured interviews with controllers. The weights are based on observations of minimum event processing times (to reflect processing times during the busiest periods).

7. Status of the Model: This model constitutes a part of work performed at the Stanford Research Institute on issues related to controller workload and to sector capacity estimation.

8. Quality of Documentation: The paper is well-written. However, several details of the model are vague and some of the more difficult issues are only lightly discussed.

9. Extent of Model Validation: The model is based on observations of minimum duration of traffic events. The frequency of occurrence of "routine" traffic events was obtained from one high altitude sector, and subsequently validated by field studies at four other en route sectors. Subsequent applications to terminal area departure sectors indicated a need to determine new frequency factors for these routine events. Sector capacities for a given sector were determined from subjective assessments by controllers and peak traffic counts. These estimates were subsequently verified by similar evaluations at several other en route sectors.

10. Modularity and Flexibility: The general approach outlined is applicable to all sectors that possess the general characteristics (with respect to ATC technology and control philosophy) assumed by this model.

11. Evaluation: This is a very pragmatic model which includes the important traffic variables, and seems to produce repeatable results for high altitude en route sectors. A weakness in the workload measurement scheme is that it depends strongly upon the "routine" category of events which were shown to vary widely when applied to terminal area sectors. Further research is needed to build a catalog of relative frequencies of traffic events for other classes of sectors (such as departure, transition, approach, etc.). The evaluation of sector capacity, as advocated by this model, depends directly upon a subjective assessment by controllers.



#### MODEL A6.4

1. Primary Model Category: Controller Workload and Performance Models

2. Report Used to Evaluate the Model:

Title: Advanced Productivity Analysis Methods for Air Traffic Control Operations

Authors: P.L. Tuan, H. S. Proctor, G. J. Couluris

Agency: Stanford Research Institute, Menlo Park, California

Report #: FAA-RD-76-164

Date: December 1976

Other I.D.: Contract No. DOT-TSC-1128

3. Author's Abstract: This report gives a description of the Air Traffic Control (ATC) productivity analysis methods developed, implemented, and refined by the Stanford Research Institute (SRI) under the sponsorship of the Federal Aviation Administration and the Transportation Systems Center. Two models are included in the productivity analysis methodology. The first is the Relative Capacity Estimating Process(RECEP) that models the traffic handling capabilities of individual ATC sectors in terms of routine, surveillance, and conflict-processing workloads. The second model is the Air Traffic Flow (ATF)\* model that simulates a multisector ATC network by tracking aircraft flows from sector to sector; and measuring traffic loadings, workload requirements, and delays under given sets of traffic input parameters and congestion relief strategy. The report covers the background and application experiences of the two models as well as technical descriptions of their input/output specifications, model structures, field data collection and reduction techniques, and potential model applications. Finally, a hypothetical example illustrating a typical RECEP/ATF application, together with post-simulation output analyses are given. A general survey of other similar models and techniques, and their comparisons with RECEP and ATF, are also included in the report.

\*This model review applies to RECEP only; for a review of ATF see Model A7.2.

#### 4. Model Description:

4.1 Model Type: Analytical; deterministic

4.2 Factors of National Airspace System Related to Model: En route sectors of ATC system, capacity of a sector, sector configuration, automation of en route ATC systems, productivity.

4.3 Input Data Requirements: The model requires input data obtained from extensive field observation of minimum times for controller tasks in handling routine and conflict events. For routine workload, there are five categories of tasks which can be associated with each routine ATC event. The model requires data on the relative frequency of these routine events, per aircraft handled, for a given type of sector. For conflict workload, the relative frequency of occurrence of conflict events is estimated as a function of traffic flow rates using the conflict generation models (A5.1 or A5.3). The model also requires the average aircraft transit time for the sector, and the average flow rate in aircraft per hour.

4.4 Outputs Obtainable: Team Workload,  $W_T$  (measured in work-minutes/hour); Radar Controller Workload,  $W_R$ , and Sector Capacity (aircraft per hour).

5. Computer-Related Characteristics: A computerized version of the model is not documented in the report. Once the required data on control event frequencies and task times are gathered for the sector, it is simple to calculate workload as a function of transit time and sector flow rate. This could be programmed for a hand calculator.

6. Major Assumptions: The model modifies earlier classifications of controller workload (see Model A6.1) by ignoring "background" workload and creating a new class called "surveillance" workload. As before, it assumes that "routine" workload varies with aircraft flow rate through the sector. Surveillance workload is assumed to vary proportionately to the average number of aircraft in the sector. From interviews with controllers, the surveillance workload coefficient is assumed to be 1.25 work-seconds per aircraft-minute. "Conflict" workload is assumed to vary with the square

of sector flow rate, with separate coefficients calculated for the overtake and crossing cases. These coefficients in turn depend on models for conflict generation which require further assumptions. (See Models A5.1 and A5.3). The maximum workload for a sector is assumed to be 66 work-minutes per hour for a two-person team, or 48 work-minutes per hour for the radar controller position. These values are based upon samples of estimates by controllers of maximum sector capacity.

7. Status of the Model: The current status of the model is not clear. The report compares this model to alternative techniques such as Work Activity\* and Work Pace\* measurement, and the Voice Channel Utilization model developed by Princeton University (Model A5.5). There does not appear to be any formal adoption of this model by the FAA as a standard technique.

8. Quality of Documentation: There is no documented computer program. The methodology is clearly and completely described with tables showing the field data from Los Angeles and Atlanta.

9. Extent of Model Validation: There does not appear to be any formal validation of the RECEP workload measures. They should be correlated with the Work Pace ratings for actual sectors. However, the capacity ratings which were obtained from Los Angeles sectors showed some consistency across sectors. A degree of validation is also indicated by the fact that capacity estimates for several Atlanta sectors appeared to agree with supervisory controller estimates for four out of seven sectors, and differed by only a few aircraft per hour on two of the other sectors. The capacity estimate for the remaining sector was low by five aircraft per hour. The variation of sector capacity estimates among individual controllers is not known, but would appear to be of the order of these discrepancies. Further validation work currently underway must be completed if critical automation and sector configuration issues are to be based on this methodology, but there are some reasons to be optimistic about eventual validation.

\*There are no references at this time on these techniques which have been under FAA study for several years.



10. Modularity and Flexibility: The model can be extended to cover any radar sector in the present ATC system. It is designed to enable the study of proposed changes in sector operations such as sector reconfiguration, enhanced automation devices, etc.

11. Evaluation: This model is the best available method of measuring controller workload as a function of controller activities in a sector. The concept of mental workload is rather vague, with the definition usually tailored to reflect measurable activities. In the model described here, a minimum observed task time is used as the measurable activity. Since an alternative workload rating scheme (Work Pace) exists, based on subjective assessment, it would be desirable to correlate Work Pace ratings with the RECEP measures of workload. This would provide some confidence in the use of minimum task times as a measure of controller workload.

However, the critical application of RECEP is to estimate sector capacity in terms of aircraft per hour. In a "calibration" performed at Los Angeles, controller estimates of sector capacity were used to establish the values of maximum workload. Employing the inverse process, these values of maximum workload were used to estimate capacity of various sectors at Atlanta, which were then compared to controller estimates in a "validation" study. Results of this validation study indicate that RECEP is able to estimate sector capacity within  $\pm 10$  percent. However, evaluations over a wider variety of en route and terminal area sectors would be desirable before the capability of the RECEP model to consistently estimate sector capacity with this accuracy is corroborated.

It should be noted that subjective estimates of sector capacity will not be consistent among controllers since individual skills will determine their personal capacity rating. This variance in controller estimates prevents the realization of greater precision from any analytic model which depends upon such subjective assessments for its calibration.

### MODEL A7.1

1. Primary Model Category: Models of Major Segments of the National Airspace System
2. Report Used to Evaluate the Model:
  - Title: Model Documentation Report
  - Authors: C.I. Chen and R. P. Utsumi
  - Agency: Autonetics Division, Rockwell International, Anaheim, California
  - Report #: C73-1218/201
  - Date: December 1973
  - Other I.D.: Contract No. DOT-TSC-508
3. Reviewer's Summary: This model is a simulation used to determine the capacity and delay performance of any segment of the air traffic control system. It is called a "network" model, since a network structure consisting of nodes and connecting branches is used to represent the structure of the ATC system. The model defines each significant point along an aircraft's path as a node (whose location and other important characteristics which may affect the model operation are specified). A node can correspond to points on the flight path or on the ground. Nodes are connected by arcs which usually represent air route segments.

The simulation moves aircraft along routes in the airspace, and on the ground, according to prespecified flight plans, without violating the ATC separation standards which are defined for each node in the system and each pair (of all possible combinations) of aircraft classes. A series of Monte Carlo (probabilistic) runs are used to predict system capacity and delay as a function of ATC system parameters, for each specified scenario. The simulation is of the "discrete event" (or "event-paced") type.
4. Model Description:
  - 4.1 Model Type: Simulation; probabilistic
  - 4.2 Factors of National Airspace System Related to the Model: Simulates sections of the National Airspace System to develop

measures of system capacity and delays to users, of that portion of the system, as a function of separation standards, aircraft mix, aircraft performance, and level of demand.

4.3 Input Data Requirements: Data requirements are very extensive and fall in the following general categories: definition of aircraft classes and aircraft characteristics for each class; description of the ATC network under consideration (node locations, node classes, air routes, etc.); specification of separation standards for each node and for each aircraft class pair; specification of demand data (rates at which aircraft of each aircraft class are generated for each route); simulation control inputs (duration of simulation, outputs desired, etc.).

4.4 Outputs Obtainable: Several different levels of output detail are available. The most detailed outputs can include the event time for all events. The second level of output gives the completion time of each flight, including the route number and aircraft class. The next level provides statistical data such as average travel time per flight, average delay, etc.

5. Computer-Related Characteristics: The simulation program is written in FORTRAN. It occupies 24756 bytes of memory space for program storage and has been run on an IBM370 at Rockwell International. The total memory required for processing a job is 226k-bytes. The maximum network size the model is capable of handling is 100 nodes, 50 routes and 500 active aircraft. The compilation time is about 11 seconds.

6. Major Assumptions: Appearances of aircraft at each "source" node of the simulated network (a source node is a node from which one or more flights originate) are assumed to occur randomly (i.e. according to a Poisson process). The movement of aircraft in the network from that point on is deterministic (determined by the speed of the aircraft), each aircraft proceeding according to a flight plan. The only deviations that can occur from the flight plan are due to conflicts between aircraft at nodes (i.e., if aircraft proceeded according to the flight plan they would violate the separation standards at that node). Service at each node/



service point is provided on a strictly first-come, first-served basis. No provision is included for controller workload limitations, i.e., aircraft proceed on their routes as long as they are sufficiently separated from each other, irrespective of how many aircraft are simultaneously active in any particular ATC jurisdictional area.

7. Status of Model: The model was developed as part of the Advanced Air Traffic Management System (AATMS) study. It is not known whether the model was used in connection with other projects following the AATMS study.

8. Quality of Documentation: Model documentation is extensive, although not particularly well-organized, and explains in detail the underlying logic. A User's Guide includes flow charts, a program listing, description of input and output statements and a very helpful example.

9. Extent of Model Validation: No attempt to validate the model's results through comparison with actual field data is reported.

10. Modularity and Flexibility: The simulation program is well-designed for modularity. However, the model is an inflexible one when it comes to deviations from its main conceptual frame, that of a microscopic, highly-detailed simulation of events on the network. Higher levels of aggregation are impossible to implement within the existing model structure.

11. Evaluation: This is an interesting model in that it amply demonstrates the model size (or model complexity) problems that one runs into when a highly faithful-to-reality simulation of any extensive segment of the ATC system is attempted. It is significant that a model with only 100 nodes and 50 routes (a modest-size network by ATC standards) requires about 230,000 bytes of memory. The preparation of inputs for the model is also a very difficult and time-consuming task, in that it requires separation standard calculations for every node in the network.

In light of this, it is believed that it is unrealistic to expect this model to be useful for any but very modest-size,

local-scale problems. More macroscopic approaches, such as the one advocated by Model A7.2, seem much more promising. However, the model's logic does incorporate several interesting features which might be useful to those involved in future research on modeling major segments of the National Airspace System.

## MODEL A7.2

1. Primary Model Category: Models of Major Segments of the  
National Airspace System

2. Reports Used to Evaluate the Model:

i) Title: Capacity and Productivity Implications of En Route  
Air Traffic Control Automation

Authors: G. J. Couluris, R. S. Ratner, S. J. Petracek,  
P. J. Wong and J. M. Ketchel

Agency: Stanford Research Institute, Menlo Park, California

Report #: FAA-RD-74-196

Date: December 1974

Other I.D.: Contract No. DOT-FA70WA-2142

ii) Title: Aggregate Flow Model for Evaluating ATC Planning  
Strategies

Authors: P. J. Wong, G. J. Couluris, and D. K. Schmidt

Agency: Stanford Research Institute, Menlo Park, California;  
Purdue University, West Lafayette, Indiana

Report #: Journal of Aircraft, Volume 14, No. 6, pp. 527-532

Date: June 1977

iii) Title: Advanced Productivity Analysis Methods for Air  
Traffic Control Operations

Authors: P. L. Tuan, H. S. Proctor and G. J. Couluris

Agency: Stanford Research Institute, Menlo Park, California

Report #: FAA-RD-76-164

Date: December 1976

Other I.D.: Contract No. DOT-TSC-1128

3. Author's Abstract: An aggregate traffic flow model (ATF) is developed and used to evaluate the potential benefits of automated, facility-level, on-line air traffic flow control. Most present air traffic models simulate, in varying levels of detail, the movement of individual aircraft which results in considerable computational requirements. However, the model described here essentially monitors and dynamically adjusts traffic flow rates and traffic densities on the routes in the ATC network. The route flow adjust-



ments are based on controller workload criteria, with the intent of eliminating traffic surges and the associated periods of excessive workload. The model is used to evaluate two flow control strategies with respect to aircraft delay, controller workload, and staffing considerations at Los Angeles Air Route Traffic Control Center.

4. Model Description:

4.1 Model Type: Simulation; deterministic

4.2 Factors of National Airspace System Related to Model: Relates traffic flow rates, air route network configuration and controller workload to aircraft travel times and aircraft delays in the National Airspace System.

4.3 Input Data Requirements: Air route network structure for the group of ATC sectors under study; hourly flow rate of aircraft by route through the network; sector workload coefficients for the sectors under study; ATC flow-control planning strategy.

4.4 Outputs Obtainable: Average delay per aircraft passing through the multi-sector group; multi-sector manning (controller) requirements; controller productivity (measured in aircraft per man-shift).

5. Computer-Related Characteristics: For a 40 sector model (the approximate size of an entire ARTCC) a core requirement of 43,000 octal words is mentioned. Typical running times for a case involving 9 sectors, 25 routes, and simulation of 9 hours of real time (involving about 1,000 aircraft), is placed at 60 to 70 seconds on a CDC 6400 machine. The reports reviewed do not contain any other computer-related information (e.g., program language, program length, etc.).

6. Major Assumptions: The program assumes that sector workload coefficients are available for all sectors under consideration and are used as inputs to the model. These coefficients (which eventually determine sector capacity) are those computed through Stanford Research Institute's RECEP technique for estimating controller workloads (See Model A6.4). The relationship between

workload and number of aircraft in a sector is approximated by a linear function.

A common average speed is assumed for all aircraft, so that average sector transit times are common to all aircraft on any given route. It is also assumed that the arrivals of aircraft at a sector, at any given hour, are distributed uniformly and at equal intervals within the hour.

Local (intra-sector) traffic is represented as travelling on "pseudo-routes" and, therefore, does not affect inter-sector traffic in any way other than the additional workload that it imposes on controllers.

7. Status of Model: It is not known whether the model has been used in contexts other than the illustrative example for the Los Angeles ARTCC presented in the first two reports (see item 2 above). It is mentioned that the multi-sector Los Angeles model could conceivably be expanded to cover the entire National Air-space System (approximately 400 sectors), but no information is available on whether such an expansion has been attempted.

8. Quality of Documentation: The basic assumptions and workings of the model are well explained and the illustrative example is especially helpful. Unfortunately, the two flow control strategies discussed are poorly explained, and the reader is not told what exactly the model does to deal with sector congestion. No flow charts or computer program listing are provided in the reports reviewed.

9. Model Validation: No information is provided on any attempts to validate this model with field data.

10. Modularity and Flexibility: The model appears to be both modular and flexible in most respects. It is clear that several of the assumptions mentioned in item 6 can be modified without requiring a major revision of the model.

11. Evaluation: This model can be viewed as a "first cut" at the development of techniques for the macroscopic (or "aggregate level") examination of problems involving multi-sector interactions.

The most interesting aspect of the model is the network structure that it suggests for representing a network of air routes in a computer. This structure can model transitions from airport-to-low altitude sectors-to high altitude sectors (and vice-versa) in a natural and easy-to-program manner. On the other hand, development of the inputs required for the specific applications of the model which are discussed in the referenced reports, would seem to be a time-consuming procedure that, at times, would necessitate making some rather arbitrary assumptions.

While the specific results reported for these models cannot be considered particularly reliable (as they seem to be intended as an illustration of how the model works rather than as an in-depth analysis of Los Angeles ARTCC operations), it is believed here that the approach described is a highly promising one and worth pursuing further.



MODEL A7.3

1. Primary Model Category: Models of Major Segments of the National Airspace System
2. Report's Used to Evaluate the Model:
  - i) Title: The Airport Network Flow Simulator  
Author: Juan F. Bellantoni  
Agency: U.S. Department of Transportation, Transportation Systems Center  
Report #: FAA-ASP-78-9  
Date: October 1978  
Other I.D.: None
  - ii) Title: The Airport Network Flow Simulator  
Author: Steven Gordon  
Agency: U.S. Department of Transportation, Transportation Systems Center  
Report #: FAA-ASP-75-6  
Date: May 1976  
Other I.D.: Performing Organization Report No. DOT-TSC-FAA-75-26
3. Reviewer's Summary: This model represents a continuation of the earlier work of Gordon (see second of the references above), including an expansion of the data base from 9 to 665 airports, as well as several improvements on Gordon's methodology.

The concern is with two types of delay: that which is directly suffered by a flight during the departure and landing phases of a flight leg (type A delay); and the delay that propagates through the air transportation network due to late gate departures by delayed aircraft (type B delay). The model includes a pre-processor algorithm, and a linkage algorithm, which is designed to prepare a daily flight schedule for each and every commercial aircraft flying in the continental United States on any given day. The flight schedule for each aircraft consists of all the flight legs that this aircraft will fly, the sequence of airports that it will visit, and the scheduled arrival and departure times for

each airport. The main part of the computer model processes the flight schedules and computes A-type and B-type delay for each airport, or for any group of airports, as well as the dollar costs of these delays.

#### 4. Model Description:

4.1 Model Type: Simulation; deterministic

4.2 Factors of National Airspace System Related to Model: Projects the impact of capacity increases at individual airports on the performance of the airport system as a whole with regard to delays and to total aircraft and passenger times through the system.

4.3 Input Data Requirements: The inputs to the model comprise a large amount of data, classified into three types: a) demand data consisting essentially of all the information contained in the Official Airline Guide regarding flight arrival and departure times, aircraft type, and airlines for all airports with some commercial service in the United States (information on how many non-scheduled flights take place at each of these airports each hour is also required); b) capacity data for each airport for each hour of the day (the capacity may change over a day due to runway changes or weather changes); and c) cost data on the cost of delays to passengers (cost of lost time), and to airlines (cost of delay occurring on the ground, and of delay occurring in the air for each aircraft type).

A set of inputs for all the above items is provided to the user by the computer program. The user may select to use these inputs or substitute his own set of data.

4.4 Outputs Obtainable: Statistical information on the magnitude of Type A and Type B delays at each airport or group of airports (given in units of time) as well as the monetary costs of these delays to airlines and to passengers.

5. Computer-Related Characteristics: The computer program is written in FORTRAN (Level G, FORTRAN IV). It contains practically no machine-dependent inputs. No information is provided on typical running times or typical running costs.

6. Major Assumptions: The linkage algorithm makes several assumptions in its attempt to trace individual aircraft through a day's journey, i.e., to develop a daily schedule of flights for each aircraft. The basic assumption is that each airline attempts to minimize ground time for its fleet of aircraft. As a result, it is postulated that, for each airline, each outgoing flight at a given airport utilizes the previously arrived aircraft of the same type which has been on the ground longer than any other incoming aircraft of that type. Several other assumptions, subsidiary to or refining the basic one, are also used to draw up the flight schedule for each aircraft.

The main program assumes that for each airport, during any given hour, the runway service time for all aircraft (irrespective of type of aircraft and type of operation involved) is identical and constant. It is also assumed that service is provided on a first-come, first-served basis, and that the OAG schedule is adhered to unless the runway service times of two aircraft overlap.

7. Status of Model: Development of the model has been completed. It is indicated that the model may be used to assess the benefits of investments in airport capacity made under the 1976 Amendments to the Airport and Airway Development Act.

8. Quality of Documentation: The logic of the program and documentation of the assumptions is not particularly well presented, and several aspects of the model may thus be confusing to the reader. A program listing and a brief user's guide, together with samples of inputs and outputs, are also presented.

9. Extent of Model Validation: The linkage algorithm has been tested with data from two airlines on two separate dates. Complete aircraft itineraries generated by the model, when compared with those obtained from the airlines, were estimated to be 70% correct. However, many of the errors could be attributed to the poor quality of the data used in the validation process.

Type-B delays predicted by the model were compared with actual delay data for three airports. Predicted versus actual delays were found to be within 12 percent for ORD, 54 percent for SFO, and



2 percent for DEN. However, adjustments in model parameters with regard to runway service times were necessary to achieve this level of agreement.

10. Modularity and Flexibility: The model as written, is self-sufficient. Changing the program to accommodate a different set of assumptions regarding the linkage algorithm would seem to be a difficult task.

11. Evaluation: This model represents a major improvement with respect to the earlier version of the model (see the second reference under item 2). The data base and potential coverage (in terms of number of airports) of the model has been expanded tremendously and the logic of the model has also been made much more plausible. However, the model still suffers from weaknesses, the most important of which may be the way in which it calculates arrival and departure delays. The linkage algorithm cannot be considered validated. Certain of the data used (non-scheduled demand, airport capacities, load factors, percentages of continuing passengers by airport) are also of questionable reliability. In summary, this model is interesting and original as a concept, but at this stage, rather crude and unreliable. It should be considered for further improvement in the future. It is the only existing model, to our knowledge, which attempts to account for the propagation of delay through a national network of airports.

MODEL A7.4

1. Primary Model Category: Models of Major Segments of the National Airspace System
2. Reports Used to Evaluate the Model:
  - i) Title: The 1972 Los Angeles Basin Standard Traffic Model; and User's Manual for the Los Angeles Basin Standard Traffic Model  
Authors: F. M. Willett, Jr.; S. Cohen and F. Maginnis  
Agency: NAFEC and The MITRE Corporation  
Report #: FAA-RD-73-90 and FAA-RD-73-88  
Date: June 1973 and April 1973  
Other I.D.: MITRE Project 934A; MITRE Report MTR-6377
  - ii) Title: Statistical Summary of the 1983 Los Angeles En Route Center Standard Traffic Model  
Author: S. Cohen  
Agency: The MITRE Corporation  
Report #: MTR-6676  
Date: October 1974  
Other I.D.: None
  - iii) Title: Statistical Summary of the 1982 Los Angeles Basin Standard Traffic Model, Vols. I and II; and User's Manual for the Los Angeles Basin Standard Traffic Model  
Authors: S. Cohen and F. Maginnis; M. Hildenberger  
Agency: The MITRE Corporation  
Report #: FAA-RD-73-87, I and II; FAA-RD-73-89  
Date: April 1973 and May 1973  
Other I.D.: MITRE Report No. MTR-6387
  - iv) Title: The 1973 Los Angeles Air Route Traffic Control Center's Air Traffic Model  
Author: F. M. Willett, Jr.  
Agency: National Aviation Facilities Experimental Center, Federal Aviation Administration  
Report #: FAA-NA-74-11

Date: 1974

Other I.D.: None

- v) Title: Advanced Air Traffic Management System B: 1995 Los Angeles Basin Traffic Model, Vols. I and II.

Author: A. D. Mundra

Agency: The MITRE Corporation

Report #: MITRE Report MTR-6419

Date: March 1974

Other I.D.: MITRE Project 291A

3. Reviewer's Summary: The "models" described in the reports referenced above develop typical peak instant traffic pictures (snapshots of the airspace) for the Los Angeles Basin (lower level airspace) and Los Angeles ARTCC (en route traffic). Actual or projected snapshots are developed for 1972, 1982 and 1995 for the terminal areas and lower level airspace, and for 1973 and 1983 for the Los Angeles ARTCC. Each aircraft, in each snapshot, is associated with a listing of all the characteristics of this aircraft (e.g., identification, position, velocity, etc.). Each snapshot is available on magnetic tape.

4. Model Description:

4.1 Model Type: Simulation; deterministic

4.2 Factors of National Airspace System Related to Model: Provides instantaneous representation of air traffic and its characteristics at selected locations and time frames.

4.3 Inputs Required: Not applicable: each traffic model/snapshot is completely prespecified.

4.4 Outputs Obtainable: For each aircraft, in each snapshot, an associated list provides: aircraft identifier; position vector (x-y-z coordinates); velocity vector; turn rate; time of flight initiation; arrival airport; departure airport; aircraft type; user class (general aviation, air carrier, military); engine category; type of propulsion; ATC status (IFR vs. VFR); and flight type (over-flight, intra-sector, etc.).



5. Computer-Related Characteristics: The model data are recorded on 9-track magnetic tapes at 800 BPI. The tape has an IBM OS/360 standard label set and contains one data set.
6. Major Assumptions: The 1972 and 1973 models are based on actual field data. Future models/snapshots are based primarily on FAA annual aviation activity forecasts, and a number of assumptions on how these annual forecasts relate to instantaneous aircraft counts. Airspace limitations and aircraft technology forecasts have also been considered in developing future snapshots.
7. Status of Model: The magnetic tapes on which the various snapshots are recorded are available to interested users through the FAA. It is not known to what extent these models have been used in connection with ATC-planning studies.
8. Quality of Documentation: The documents describing the various models/snapshots clearly outline the contents of each tape.
9. Extent of Model Validation: The 1972 and 1973 models/snapshots are based on actual data. There is no way to validate the future traffic representations in advance.
10. Modularity and Flexibility: Does not apply: the contents of each instantaneous traffic representation are prespecified and not subject to modification.
11. Evaluation: The various instantaneous traffic representations reviewed here are not models, strictly speaking, since by themselves they do not provide any analytical and/or simulation capability. They should rather be viewed as providing convenient testbeds for the exercise of other analytical or simulation models. For instance, a model oriented toward the estimation of the number of inter-aircraft conflicts in an ATC environment might be tested with one of the scenarios of the Los Angeles traffic.

The projected snapshots may be taken to represent future traffic scenarios, without attaching any significance to the specific year in which they are forecasted to occur.

## MODEL B1.1

1. Primary Model Category: Safety-Related Models

2. Report Used to Evaluate the Model:

Title: Parallel Runway Spacing

Author: Per A. Kullstam

Agency: Computer Sciences Corporation

Report #: Navigation, Vol. 19, No. 1, pp. 19-28

Date: Spring 1972

Other I.D.: None

3. Reviewer's Summary: This model examines a parallel runway landing case for which the minimum runway spacing is to be established, while ensuring an extremely low collision risk. The model is based on a continuous surveillance and control concept which does not require any knowledge about the tails of the probability distributions of aircraft location to establish the collision risk.

The situation is broken down into parametric investigations of two airspace zones: the Normal Operating Zone (NOZ) and the Intervention Zone (IZ). The IZ is sized in such a way that the penetration probability of this zone by an aircraft will be sufficiently small to ensure the required collision risk. The IZ includes an airspace for detection as well as the necessary airspace for the recovery maneuver. The NOZ is sized to provide a low intervention rate.

The model yields the sensitivity and trade-offs between various system parameters in establishing a closely-spaced parallel runway system.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates the performance of the navigation, surveillance and control subsystems, as well as aircraft mix and aircraft characteristics, to lateral separation standards on final approach, and to ATC safety.

4.3 Input Data Requirements: Surveillance equipment update rate and accuracy; maximum acceptable penetration probability for intervention zone; blunder angle; aircraft/pilot performance and characteristics; ground controller/pilot communication delay; turn rate and aircraft velocity; maximum acceptable intervention rate; width of normal operating zone.

4.4 Outputs Obtainable: Parametric sensitivity analysis of changes in the required spacing between runways as one or more of the input variables are changed systematically.

5. Computer-Related Characteristics: The relationships developed are all analytical and simple to evaluate numerically. While use of a computer may be desirable for computing numerical values, such use is not really required and is not discussed in the referenced document.

6. Major Assumptions: The model assumes knowledge (perhaps approximate) of the values of the many parameters required as inputs, and that target levels of safety can be stated, either explicitly or implicitly (e.g., by comparison with current levels of safety). The model also assumes continuous surveillance of aircraft during final approach.

7. Status of Model: No information is provided as to whether this model has been used in connection with assessments of ATC system safety or in the establishment of minimum parallel runway separation standards.

8. Quality of Documentation: The logic of the model and the mathematical derivation of the various expressions are very well presented. The examples given are helpful in comprehending the material.

9. Extent of Model Validation: No information is presented on any attempt to validate any aspects of the model.

10. Modularity and Flexibility: The model is an analytical one and, consequently, quite flexible (once its basic premises are accepted). The model can be easily modified for different sets of assumptions regarding the blunder scenario that the model uses.



11. Evaluation: This model is strikingly similar to one due to Haines (Model B1.2) for lateral spacing between parallel runways. Although the two models vary somewhat in the degree of emphasis that they place on the various parameters examined and in some model details, their basic philosophies are virtually identical (as is the gist of the mathematical analyses that they contain). The documentation of this model (in terms of logic description and discussion of assumptions) is superior to that of Model B1.2, and it is recommended that potential users study the referenced paper by Kullstam first, regardless of whether they wish to use Model B1.1 or B1.2.

In general, the approach provided here is a highly practical one for evaluating a lateral separation standard between runways. It may, however, be overly optimistic to expect that the extensive set of inputs that the model requires will be readily available. Setting targets for such parameters as the penetration probability for the intervention zone, or the maximum intervention rate, is also a highly sensitive matter.

## MODEL B1.2

1. Primary Model Category: Safety-Related Models

2. Report Used to Evaluate the Model:

Title: Reduction of Parallel Runway Requirements

Author: Andrew L. Haines

Agency: The MITRE Corporation

Report #: MTR-6841

Date: January 1975

Other I.D.: None

3. Reviewer's Summary: The model described in this report is intended as a tool for evaluating the adequacy of lateral separations between parallel runways. A blunder situation is analyzed under worst case conditions, and the spacing between runway centerlines is chosen to achieve a prespecified level of performance with regard to safety. The model provides for: a normal operating zone (NOZ) in which landing aircraft should normally operate; a detection zone (DZ) for the purpose of detecting an aircraft's departure from the NOZ (with a specified maximum probability of nondetection of a blunder within this zone); a correction zone (CZ) to compensate for the continued motion of the blundering aircraft during reaction time; a "gain zone" (GZ) which allows the non-blundering aircraft to take evasive action; and a miss distance zone which consists of both a specified minimum miss distance (MD) and a navigation buffer (NB) to account for the possible deviations of the nonblundering aircraft around the ILS center line. The required runway spacing (RS) is then given by  $NOZ + DZ + CZ + MD + NB - GZ$ . The required lateral dimension of each of these zones can be estimated from the input parameters to the model, once the required performance standards (with regard to safety) are specified.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates the performance of the navigation, surveillance and control subsys-

tems, as well as aircraft mix and aircraft characteristics, to lateral separation standards on final approach and, thus, to the safety level of the ATC system.

4.3 Input Data Requirements: Traffic mix; surveillance equipment update rate and azimuth accuracy; maximum blunder angle; maximum acceptable nondetection probability for detection zone; minimum acceptable miss distance; turn rate and aircraft velocity; navigation accuracy; type of surveillance in effect; width of normal operating zone.

4.4 Outputs Obtainable: Level of safety associated with a given runway spacing; or, conversely, runway spacing associated with a given level of safety. In the examples given, the level of safety is implied by the maximum acceptable probability of false alarms (MAX PFA).

5. Computer-Related Characteristics: This is essentially an analytical model and, while use of a computer may be desirable for computing numerical values, such use is not really required. Since, computer-related issues are entirely secondary they are not discussed in the referenced document.

6. Major Assumptions: The model assumes knowledge (perhaps approximate) of the values of the many parameters required as inputs and that target levels of safety can be stated, either explicitly or implicitly (e.g., by comparison with current levels of safety). The model also assumes continuous surveillance of aircraft during final approach.

7. Status of Model: No information is provided as to whether this model has been used in connection with assessments of ATC system safety or in the establishment of minimum parallel runway separation standards.

8. Quality of Documentation: The logic of the model and the mathematical derivation of the various expressions are quite well presented, although too briefly at times. The difficulty of obtaining input values is underplayed. The examples given are helpful in comprehending the material.



9. Extent of Model Validation: No information is presented on any attempt to validate any aspects of the model.

10. Modularity and Flexibility: The model is an analytical one and, consequently, quite flexible once its basic premises are accepted. The model can be easily modified for different sets of assumptions regarding the blunder scenario that the model uses.

11. Evaluation: This model's philosophy is entirely similar to that of the lateral separation model of Kullstam (see Model B1.1), and of the longitudinal separation model of Haines (see Model B1.3). It provides a highly practical approach to evaluating separation standards. It may, however, be overly optimistic to expect that the extensive set of necessary inputs (some requiring rather arbitrary decisions on the part of the ATC planners) will be available. Setting targets for levels of safety (even in the innocuous form of false alarm probabilities) is also a highly sensitive undertaking. This model represents the state-of-the-art with regard to lateral separations on final approach.

### MODEL B1.3

1. Primary Model Category: Safety-Related Models

2. Reports Used to Evaluate the Model:

- i) Title: Concepts for Determination of Longitudinal Separation Standards on Final Approach

Author: A. L. Haines

Agency: The MITRE Corporation

Report #: MTR-7047

Date: October 1975

Other I.D.: Contract No. DOT-FA70WA-2448

- ii) Title: Longitudinal Separation Standards on Final Approach for Future ATC Environments

Authors: A. N. Sinha and A. L. Haines

Agency: The MITRE Corporation

Report #: MTR-6979

Date: October 1975

Other I.D.: Contract No. DOT-FA70WA-2448

3. Reviewer's Summary: A model is described for evaluating the minimum longitudinal separation standard for aircraft on final approach to the same runway. The approach taken is that of analyzing a worst case, and providing sufficient separation so that the probability of collision becomes extremely small. The model actually is not concerned with probability of collision per se, but instead with providing a longitudinal space (the "detection zone") which is sufficiently large that a major blunder will not go undetected. The detection zone is added to: separations intended to account for runway occupancy times and for wake vortex avoidance; additional spacing to account for speed and size differences among aircraft; and a metering and spacing buffer to arrive at a nominal separation target at runway threshold for any given pair of successive aircraft on final approach.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

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REVIEW AND EVALUATION OF NATIONAL AIRSPACE SYSTEM MODELS.(U)  
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4.2 Factors of National Airspace System Related to the Model:

Relates the performance of the navigation, surveillance and control subsystems as well as aircraft mix and aircraft characteristics, to longitudinal separation standards on final approach and, thus, to the safety level and capacity of the ATC System.

4.3 Input Data Requirements: Data acquisition system update interval and range accuracy; aircraft class characteristics such as mean and standard deviation of runway occupancy time, approach and final velocity on landing, and wake vortex protection requirements; length of final approach and glide path; maximum acceptable probability of nondetection of aircraft blunder; blunder velocity in addition to normal closing velocity; delay in taking corrective action; standard deviation of metering and spacing error; weather conditions.

4.4 Outputs Obtainable: Minimum required separation standard at the point of closest approach between any given pair of landing aircraft on final approach; minimum spacing of the aircraft at runway threshold; recommended nominal (planned) spacing at the threshold.

5. Computer-Related Characteristics: The model is an analytical one and, while use of a computer is desirable for computing numerical values, such use is not essential. Since computer-related issues are entirely secondary, they are not discussed in the referenced documents.

6. Major Assumptions: It is assumed that an acceptable probability of nondetection of a blunder within the detection zone can be stated. Knowledge of the approximate values of the required inputs is also assumed as well as continuous surveillance of aircraft during final approach. The model considers runway occupancy times and wake vortex protection as the two possible limiting factors for longitudinal separation. It assumes that such considerations as ILS interference, communication channel congestion, beacon system garbling, and controller workload (on final approach) are not limiting factors in the ATC system.

7. Status of Model: No information is provided on whether this model has been used in connection with assessments of the adequacy or potential for reduction of present or future ATC longitudinal separations on final approach.
8. Quality of Documentation: The logic of the model and the accompanying analysis are adequately (but briefly) presented. The examples given are helpful.
9. Extent of Model Validation: No information is presented on any attempt to validate any aspects of the model or its predictions. The sample results presented appear logical and internally consistent.
10. Modularity and Flexibility: The model can be easily modified to account for additional limiting factors (such as controller workload) that may arise in the future, as well as for major changes in the values of some of the input parameters.
11. Evaluation: This is a highly practical model that can be easily applied to obtain good theoretical estimates for desirable longitudinal separations on final approach. It is believed that the major difficulty in attempting to implement findings derived from the model (e.g., recommendations on reducing separations) would be obtaining agreement on the correctness of the input values used and on setting a value for PND (the probability of nondetection). The model is also a useful tool as a first step in performing runway and airport capacity analyses, since such capacity is largely determined by the longitudinal separation standards in use.

MODEL B1.4

1. Primary Model Category: Safety-Related Models

2. Reports Used to Evaluate the Model:

- i) Title: Computer Simulation Study of Air Derived Separation Assurance Systems in Multiple Aircraft Environments

Authors: J. M. Holt and G. R. Marner

Agency: Collins Radio Company, Cedar Rapids, Iowa

Report #: SRDS No. RD-69-31

Date: October 1969

Other I.D.: Contract No. FA-WA-4598, Project No. 241-DO3-01CC

- ii) Title: Separation Hazard Criteria

Authors: J. M. Holt and G. R. Marner

Agency: Collins Radio Company

Report #: Report of Air Traffic Control Advisory Committee, Department of Transportation, Vol. 2, Appendix C4

Date: December 1969

Other I.D.: None

- iii) Title: Separation Theory in Air Traffic Control System Design

Author: J. M. Holt and G. R. Marner

Agency: Collins Radio Company

Report #: Proceedings of the IEEE, Vol. 58, No. 3

Date: March 1970

Other I.D.: None

- iv) Title: Safe Separation in Controlled Flight

Author: J. M. Holt

Agency: McDonnell Douglas Electronics Company, St. Louis, Missouri

Report #: Navigation, Vol. 21, No. 1, pp. 1-8

Date: Spring 1974

Other I.D.: Contract No. DOT-TSC-144

3. Reviewer's Summary: The basic model developed in these reports



provides a framework for analyzing the collision hazards associated with any given position-velocity configuration of a pair of aircraft in any specified navigation, surveillance and control environment. The model takes into account position and velocity errors, computer and communication lags, and pilot/aircraft response delays. In addition, the model examines various hazard detection and conflict resolution strategies for each given case. All these considerations define position and velocity thresholds which represent the last chance for effective intervention by air traffic controllers or by various types of collision avoidance equipment. The future position boundaries of the aircraft, as defined by these thresholds, serve to specify the minimum separations tolerable to the ATC system in each given case.

#### 4. Model Description:

4.1 Model Type: Analytical; deterministic

4.2 Factors of National Airspace System Related to Model: Relates aircraft characteristics and the performance of the navigation, surveillance and control subsystems of the ATC system to separation requirements and, therefore, to the safety level of the system.

4.3 Input Data Requirements: Surveillance system update interval and accuracy; navigation accuracy; aircraft flight characteristics; freedom allowed by ATC with regard to aircraft acceleration; minimum desirable aircraft passing (miss distance); controller/pilot performance and maneuver delay; degree of "cooperativeness" of aircraft involved in a hazardous situation; constraints on possible aircraft movements during conflict resolution.

4.4 Outputs Obtainable: Dimensions of required protected region around each aircraft, for each particular scenario under consideration.

5. Computer-Related Characteristics: This is an analytical model providing the framework for mathematical analysis of various given situations. Use of a computer is needed only to perform extensive parametric and sensitivity analyses with the mathematical expressions derived from the model.

6. Major Assumptions: The model examines the separation standard/collision hazard problem from a deterministic rather than probabilistic point of view. This implies that the analysis is carried out under the assumption that desirable levels of safety can be specified (in terms of probabilities of penetration of protected regions), from which separation standards and hazard thresholds can be derived. It also assumes that worst case analysis (irrespective of the likelihood of such worst cases) will be used to determine these standards and thresholds.

7. Status of Model: A version of this model was used in connection with the work of the 1969 ATC Advisory Committee of the Department of Transportation. Analysis using the model led to the Committee's conclusion that "an air-derived Collision Avoidance System that exchanges only range and range-rate has an alarm region that is greater under certain circumstances than current separations under VFR and even IFR conditions." We have no information as to whether this type of model is currently in use in connection with ongoing studies of ATC safety.

8. Quality of Documentation: The presentation of the logic and the mathematical analysis is clear and precise (in all related documents). The third and fourth documents referenced above are particularly well-written, and are sufficient for an initial understanding of the approach taken.

9. Extent of Model Validation: No information is presented on any attempt to validate any aspects of the model(s) via an analysis of actual data.

10. Modularity and Flexibility: The model is a very general one and can be adopted to any particular set of circumstances.

11. Evaluation: This is a very general model that can be used in a wide variety of contexts. In fact, strictly speaking, it constitutes a methodological approach, or a genealogy of models rather than a single one. However, due to the fact that the approach calls for a worst-case, deterministic analysis (without consideration of probabilities for the cases examined) it may lead to

postulation of excessive separation requirements in some contexts. Therefore, in applying the model, it is advisable to adapt it to the particular set of circumstances at hand, restricting for instance the degrees of freedom regarding the future positions of aircraft in the model. In this sense, Models B1.1, B1.2, and B1.3 can be considered as simply special cases of this model, i.e., as applications of the model to the final approach phase of flight.

As indicated in item 7 above, this family of models has already been influential in determining ATC-related policy on the part of the U.S. Government. Prospective researchers on ATC safety would do well to become familiar with the analytical details of this model.



### MODEL B1.5

1. Primary Model Category: Safety-Related Models

2. Report Used to Evaluate the Model:

Title: The Calculation of Aircraft Collision Probabilities

Author: Juan F. Bellantoni

Agency: U.S. Department of Transportation, Transportation  
Systems Center, Cambridge, MA

Report #: Transportation Science, Vol. 7, No. 4, pp. 317-339

Date: November 1973

Other I.D.: None

3. Author's Abstract: The basic limitation on air traffic compression, from the safety point of view, is the increased risk of collision due to reduced separations. In order to evolve new procedures, and eventually a fully automatic system, it is desirable to have a means of calculating the collision probability for any prescribed flight paths. This model extends the statistical-probabilistic method of collision probability calculation, which has been limited to parallel, straight line flight paths, to arbitrary flight paths and vehicle shapes. The general formula is specialized to the cases of large relative velocity, non-zero relative velocity, zero relative velocity, and spherical collision surface. The formulas are applied to independent curved landing approaches to parallel runways.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates separation requirements, navigation errors and route configuration to collision probability and, consequently, to safety in the National Airspace System.

4.3 Input Data Requirements: Aircraft dimensions; separation standards; dimensions of space around aircraft that must be protected (may include allowance for protection against wake vortices); aircraft speed; aircraft routes (in detail); size of deviations

from nominal positions of aircraft (may vary with time and position of aircraft).

4.4 Outputs Obtainable: Collision risk, measured as expected number of violations of protected space around an aircraft by another aircraft over any specified period of time.

5. Computer-Related Characteristics: This is an analytical model and, therefore, computer implementation is not required (other than for computation of numerical results from the rather complicated mathematical expressions associated with the model). A computer program was written to compute the numerical results for one of the special cases that the model covers.

6. Major Assumptions: Although the general model does not assume independence of the navigation errors of different aircraft, all specific cases that are worked out make this assumption. All specific results (other than the most general expressions) are derived assuming Gaussian (normal) error distributions.

7. Status of Model: No information is provided on whether this model has been used in connection with any assessments of ATC system safety.

8. Quality of Documentation: The logic of the model and the mathematical derivation of the various expressions are well presented in the highly readable referenced paper.

9. Extent of Model Validation: No information is presented as to any attempt to validate the model with actual data.

10. Modularity and Flexibility: The model presented is a very general one and can be specialized to particular situations by making various different sets of assumptions. This is illustrated through application of the model to a small number of special situations.

11. Evaluation: This model represents an interesting and original effort, including a sophisticated and correct mathematical analysis. It attempts to develop a very general safety model that can be applied to arbitrary flight paths and all ATC environments (en

route, terminal area, final approach). This is indeed done and, as the referenced report shows, other better known models can be considered special cases of the present one. The model, however, cannot be applied in practice without specializing it to particular situations. The reason is that the data required (to apply the model in its most general form) are not likely to be available. This is particularly true of the probability density function  $W(\bar{r}, \bar{v}, t)$  for the relative position and velocity of any pair of aircraft at any time  $t$ . This probability density function is a required input for the general form of the model.



MODEL B1.6

1. Primary Model Category: Safety-Related Models

2. Reports Used to Evaluate the Model:

- i) Title: Models for Estimating the Number of Conflicts  
Perceived by Air Traffic Controllers

Authors: William J. Dunlay, Robert Horonjeff, Adib Kanafani

Agency: Institute of Transportation and Traffic Engineering,  
University of California, Berkeley, California

Report #: Special Report

Date: December 1973

Other I.D.: Contract No. DOT-FA-72-WA-2827; AD number:  
A023533

- ii) Title: Applications of Human Factors Data to Estimating  
Air Traffic Control Conflicts

Authors: William J. Dunlay, Jr. and Robert Horonjeff

Agency: Institute of Transportation and Traffic Engineering,  
University of California, Berkeley, California

Report #: Transportation Research, Vol. 8, No. 3, pp.  
205-217

Date: August 1974

Other I.D.: Contract No. DOT-FA-72-WA-2827

- iii) Title: Analytical Models of Perceived Air Traffic Control  
Conflicts

Author: William J. Dunlay

Agency: Institute of Transportation and Traffic Engineering,  
University of California, Berkeley, California

Report #: Transportation Science, Vol. 9, No. 2, pp. 149-  
164

Date: May 1975

Other I.D.: Contract No. DOT-FA-72-WA-2827

- iv) Title: On the Conflict Frequency at Air Route Intersections

Author: David K. Schmidt

Agency: School of Aeronautics and Astronautics, Purdue  
University, West Lafayette, Indiana 47907

Report #: Transportation Research, Vol. 11, No. 3, pp. 351-355

Date: August 1977

3. Reviewer's Summary: A model of en route traffic leads to mathematical expressions for the expected number of crossing conflicts and overtake conflicts per unit time, as perceived by air traffic controllers. The number of conflicts depends on route geometry, separation criteria, aircraft velocities, aircraft flow rates on the air routes, and controller perception considerations. The model shows that the expected number of conflicts increases as the square of the aircraft flow rate. The fourth report listed above extends the results of the crossing conflicts model by developing an expression for the variance of the number of conflicts. It is shown that the variance is large and this explains, in part, the appreciable variability in air traffic controller workload.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates traffic mix and characteristics, separation requirements, and controller characteristics to collision probabilities and, ultimately, to ATC system capacity and safety.

4.3 Input Data Requirements: En route minimum separation standards, traffic mix and travel speeds, geometry of air routes (including angles between pairs of air routes at intersections), and quantified information on how air traffic controllers perceive conflicts. The last item may be very difficult to provide, although the first of the reports referenced above suggests typical values for the information sought.

4.4 Outputs Obtainable: Expected values of the number of crossing conflicts and of overtake conflicts per unit time, as perceived by the air traffic controller. Variance of the number of crossing conflicts (in Schmidt report).

5. Computer-Related Characteristics: No computer programs are discussed in the reports. The mathematical expressions developed are sufficiently simple to evaluate with any good pocket calculator.

6. Major Assumptions: Traffic flow on air routes is represented as a Poisson process. That is, the instants at which aircraft cross a specific point on an air route are random in time (i.e., they are samples from a Poisson process). This assumption is said to be supported by available field data.

The model also assumes that the probability density function for the minimum conflict distance according to controller's perceptions (see the second reference under item 2) can be obtained from field data. However, any other suitable expression can be used to represent this distance in the model.

7. Status of Model: No information is provided in any of the reports as to whether this model has been used or will be used in connection with assessments of ATC system safety.

8. Quality of Documentation: The logic of the model and the mathematical derivation of the various expressions are well presented. The second and third reports referenced in item 2 are particularly readable.

9. Extent of Model Validation: No information is presented on model validation other than data related to the Poisson assumption for traffic flow on air routes.

10. Modularity and Flexibility: The model leads to easily usable, closed-form analytical expressions. These expressions can be used to estimate air route capacity and air route intersection capacity, or can be used as inputs to other models concerned with overall ATC system capacity (see Category A7) or controller workload (see Category A6).

11. Evaluation: This fine model leads to simple expressions which should provide good, first-order approximations of the expected number of crossing and overtake conflicts. The crossing conflicts model, however, is very sensitive to assumptions as to how controllers perceive such conflicts, and the numerical results are sensitive to the value of the minimum conflict distance used by controllers. The model also includes some major simplifications: for instance, with respect to crossing conflicts, the analysis does not consider



the fact that, in dense traffic, aircraft on any given air route arrive at any particular point on the route at regular intervals (due to minimum spacing) rather than randomly.

Use of this model to obtain estimates of numbers of conflicts is recommended, after the limitations of the model are properly understood. It should also be borne in mind that the model has yet to be validated against field data.

Unfortunately, this highly practical model may become less relevant as the use of Area Navigation (RNAV) grows in the United States ATC system, thus increasingly deviating from the strict airway network structure that the model assumes.

MODEL B1.7

1. Primary Model Category: Safety-Related Models

2. Reports Used to Evaluate the Model:

i) Title: Collision Risk Model for NAT Region

Author: Ronald Hershkowitz

Agency: U.S. Department of Transportation, Transportation Systems Center

Report #: DOT-TSC-FAA-71-6

Date: May 1971

Other I.D.: None

ii) Title: Analysis of Long-Range Air Traffic Systems: Separation Standards, Parts I, II and III

Author: P. G. Reich

Agency: Royal Aircraft Establishment, Great Britain

Report #: Journal of the Institute of Navigation, Vol. 19  
No. 1, No. 2 and No. 3

Date: January, April and July 1966

iii) Title: An Aircraft Collision Model

Author: Robert E. Machol

Agency: Northwestern University, Chicago, ILL

Report #: Management Science, Vol. 21, No. 10

Date: June 1975

Other I.D.: None

3. Reviewer's Summary: The model reviewed here can be used to analyze the effects of separation standards on collision risk in an uncontrolled ATC environment. The model was proposed by Reich (in the series of papers referenced above), and was subsequently modified for use in the parallel tracking system over the North Atlantic. The Hershkowitz report contains a summary technical presentation of the model, while the Machol paper, which describes the model in less technical terms, provides the history of the use of the model to establish safe separation standards over the North Atlantic.

Each aircraft in the model is represented by a box equal in length, width, and height to the dimensions of the aircraft (the "collision slab"). A collision occurs when an aircraft enters another aircraft's collision slab. The model uses numerous inputs to calculate two quantities: the collision rate, i.e., the number of collisions for each unit of time that two aircraft spend on the same or on parallel (and, theoretically nonintersecting) tracks; and the proximity time, i.e., the amount of time during a trip that each aircraft spends in "proximity" (under potential collision risk) to other aircraft. The product of collision rate, proximity time and the total number of aircraft hours, is used as an estimate of the overall frequency with which aircraft collisions can occur over a set of parallel air routes.

#### 4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates separation standards, navigation accuracy, physical dimensions of aircraft, structure of air routes, and density of traffic to the collision risk and, therefore, to the level of safety in an uncontrolled ATC environment.

4.3 Input Data Requirements: Aircraft dimensions (length, width, height); longitudinal, lateral and vertical separation standards; average speed and average relative speeds of aircraft; the probability distributions for lateral, longitudinal and vertical deviations from nominal positions; the duration of potential hazards as a function of the directions and relative positions of aircraft; the number of flying hours over which the proximity times must be calculated.

4.4 Outputs Obtainable: Collision risk, usually measured as the expected frequency of collisions for any given number of flying hours (10 million hours has been used as the base of measurement for the North Atlantic).

5. Computer-Related Characteristics: This is an analytical model and, therefore, computer implementation is a secondary issue. Due to the complexity of the mathematical expressions that are derived from the model, a computer program is necessary to obtain numerical



estimates of collision risk for any given set of input parameters. Such a program is not discussed in any of the documents reviewed.

6. Major Assumptions: The model makes three fundamental assumptions: i) No surveillance exists in the area of interest, and no provision is made for pilot-initiated collision avoidance following a visual or instrument sighting of another aircraft; ii) the navigation errors in each dimension are independent of one another; iii) the navigation errors of neighboring aircraft are statistically independent. It is also implicitly assumed that all aircraft in the region of interest experience navigational errors of similar size and character, and that these errors are independent of time and location along a route.

7. Status of Model: This model, in a variety of versions, has been used more extensively than any other ATC safety-related model. The model was the main tool that supported the work of the North Atlantic Systems Planning Group (NAT SPG) over a period of better than eight years. Derivatives of the model have subsequently supported the work of the ICAO Panel for the Review of the General Concept of Separation (RGCS Panel).

8. Quality of Documentation: The Reich model has been supported by good documentation, both in the original Reich papers and then in the fine presentation of the model and its extensions by Hershkowitz. The Machol paper is also excellently written.

9. Extent of Model Validation: The model cannot be considered validated in many of its aspects (it is, in any event, purposely conservative in its approach). However, several specific predictions derivable from the model have been confirmed by data from the North Atlantic region (see Machol paper).

10. Modularity and Flexibility: The model is rather inflexible, in the sense that it cannot be used in an environment different from the one that it was originally designed for (uncontrolled traffic on parallel tracks). However, as long as the basic scenario remains the same, the model can be used with a wide range of input parameters. It has also been used to analyze a somewhat modified

air route configuration known as the North Atlantic composite configuration.

11. Evaluation: For the purposes that it was conceived this is an outstanding model. It has also led to the collection of an enormous amount of highly useful data. Its usefulness has been amply demonstrated by the fact that the NAT SPG effort eventually led to a set of universally accepted and highly significant conclusions concerning track separations over the North Atlantic.

On the other hand, the second and third assumptions, listed in item 6 above, can be questioned, and have never been proved to be valid by actual data. The model should be extended to cover cases in which the navigational capabilities of different aircraft in a region are markedly different. This, for example, has been the case with North Atlantic traffic in recent years (with wide-body aircraft equipped with INS while conventional jets still fly using Doppler Navigation). The model has already been extended to the case where the performance of navigation systems is time- and location-dependent (see review of Model B1.8).

It is strongly recommended that the prospective user of the model read the Machol paper first (to become generally familiar with the model, its use and its strong and weak points), and then proceed to the Hershkowitz report, and finally to the Reich papers.

MODEL B1.8

1. Primary Model Category: Safety-Related Models

2. Reports Used to Evaluate the Model:

- i) Title: An ATC/Surveillance Modelling Approach for Specifying Lane Separation Standards

Authors: J. S. Tyler, D. E. Stepner, J. A. Sorensen

Agency: Systems Control, Inc., Palo Alto, California

Report #: Paper No. 10 in AGARD Conference Proceedings No. 105 on Air Traffic Control Systems, AGARD-CP-105

Date: June 1973

Other I.D.: AD760164, Contract No. DOT-TSC-260

- ii) Title: Oceanic Surveillance and Navigation Analysis, FY 72

Authors: G. A. Gagne and R. M. Hershkowitz

Agency: Transportation Systems Center, U.S. Department of Transportation, Cambridge, MA

Report #: FAA-RD-72-142

Date: August 1972

Other I.D.: AD752274; Contract No. FA-204

3. Excerpt from Author's Abstract (AGARD Paper): A model is described which has the same general input/output format as the well-known Reich model (see Model B1.7) that has been used for specifying North Atlantic route separations. However, two significant extensions to the Reich model are included: (1) the time-varying nature of the aircraft position errors (and, therefore, collision risk) is modeled and (2) the capability of including an independent surveillance system is modeled.

Numerical results are presented that show the impact of inertial navigation systems (INS) and satellite surveillance on the separation standards and safety of the North Atlantic route structure. It is shown, for example, that INS only will probably support a 45 n.mi. lateral separation, whereas INS with a satellite surveillance will probably support less than a 30 n.mi. lateral separation. The use of this modeling technique for determining the sensitivity of system



parameters such as navigation accuracy, surveillance accuracy and fix rate, and alarm thresholds to airway safety is also illustrated.

4. Model Description:

4.1 Model Type: Analytical; probabilistic

4.2 Factors of National Airspace System Related to Model: Relates separation standards, navigation accuracy, surveillance update rate and accuracy, and ATC procedures (as well as the physical dimensions of aircraft and density of traffic) to collision risk in a parallel route structure and, therefore, to the level of safety.

4.3 Input Data Requirements: Surveillance update interval and accuracy; navigation accuracy; lateral, longitudinal and vertical separation standards; alarm threshold for controller intervention; heading angle and velocity used to return to desired position after controller intervention; aircraft proximity times; aircraft dimensions and speeds; relative cross-track velocities; frequency and probability of overlap of the z-coordinates of aircraft on parallel tracks.

4.4 Outputs Obtainable: Collision risk, usually measured as the expected frequency of collisions for any given number of flying hours (10 million hours is often used over the North Atlantic).

5. Computer-Related Characteristics: This is an analytical model and, therefore, computer implementation is a secondary issue. Due to the complexity of the mathematical expressions that are derived from the model, a computer program is desirable in order to facilitate obtaining numerical estimates of collision risk for any given set of input parameters. Such a program is not discussed in the document reviewed.

6. Major Assumptions: The model makes three fundamental assumptions: i) navigation errors in each dimension are independent of each other; ii) navigation errors of neighboring aircraft are statistically independent; iii) collisions can occur only between aircraft assigned to pairs of neighboring tracks. The assumptions considering the shape of the "tails" of the navigation and surveillance errors (i.e., the shape of the errors' probability density functions at their

extreme ends) are not spelled out in the reviewed report. These errors are allowed to vary as a function of time and location along a route. It is implicitly assumed that all aircraft of interest experience navigational errors of similar size and character (e.g., all are equipped with INS).

7. Status of Model: No information is available on the current status of the model or on whether it has ever been applied for other than illustrative purposes.

8. Quality of Documentation: The documents reviewed are vague on the details of the mathematical analysis and on some of the main technical assumptions of the model.

9. Extent of Model Validation: No indication is given of any attempt to validate any aspects of this model by comparison with actual data. The input parameters used for the sensitivity analyses are derived from the North Atlantic study of the late 1960's.

10. Modularity and Flexibility: Although a claim to the contrary is made, it is difficult to see how this model can be applied in contexts other than the oceanic one, since the logic of the model is geared to sizes of input parameters similar to those encountered in oceanic flights.

11. Evaluation: This model attempts to extend the Reich model (Model B1.7) to an environment in which a surveillance capability is present. The validity of this concept is very questionable. The Reich model by its nature is strongly oriented to uncontrolled environments. Once a surveillance capability is present, the assumption that individual aircraft fly independently over long periods of time is not realistic. That is, neighboring aircraft can be controlled as a group, thus invalidating the most basic assumption of the Reich model which calls for independence among neighboring aircraft.

In addition to this fundamental objection, the whole premise of explicitly evaluating probabilities of the size of  $10^{-10}$  and smaller (on the basis of sets of assumptions regarding the shape of the tails of probability density functions for navigational and surveillance

accuracy) does not inspire much confidence in the results. A more valuable extension of the Reich model would be one that computes collision risk when, in an uncontrolled environment, the navigational capabilities of different groups of aircraft are not the same.

The most valuable contribution of the model reviewed here can be said to be the extension of Reich's model to the case where navigation system errors are time- and location-dependent.

The technical contents of the two documents reviewed are almost identical, with the second document referenced above being more detailed.



MODEL B1.9

1. Primary Model Category: Safety-Related Models

2. Report Used to Evaluate the Model:

Title: Studies of Uncontrolled Air Traffic Patterns

Authors: E. G. Baxa, Jr., L. L. Scharf, W. H. Ruedger, J. A. Modi, S. L. Wheelock, C. M. Davis

Agency: Research Triangle Institute, Research Triangle Park, N.C.

Report #: NASA CR-141397; also RTI 43U-840

Date: April 1975

Other I.D.: Contract NAS6-2312, Phase I

3. Reviewer's Summary: An analytical model is developed for estimating collision probabilities for aircraft operating in an uncontrolled terminal area environment. Parts of the model are complete while others are imprecise. It is assumed that, prior to landing, aircraft in this environment (obviously flying under VFR conditions) follow a rectangular landing pattern centered at the arrival runway. This is called the Basic Standard Approach Pattern. Aircraft may enter this landing pattern at a small number of pre-specified entry points. Aircraft enter the pattern at random instants in time, described in the model by a (homogeneous or nonhomogeneous) Poisson process. Under a number of assumptions regarding: i) what other aircraft in the pattern are visible or invisible to a pilot in any given aircraft; and ii) how much time a pilot spends looking for other aircraft, an expression can be derived for the probability of a collision between two aircraft. A simulation program is then used to generate aircraft and aircraft tracks (along the rectangular pattern of interest). Using a variety of measures, such as "the number of times two aircraft are within a given distance of each other" or "pilot workload", inferences can be made concerning the level of safety associated with different demand levels, pilot procedures and demand patterns along the prescribed tracks.

4. Model Description:

- 4.1 Model Type: Analytical with some simulation; probabilistic
- 4.2 Factors of National Airspace System Related to Model: Relates traffic density and flight procedures in an uncontrolled terminal area environment to flight safety.
- 4.3 Input Data Requirements: Characteristics of air traffic in terms of entry points, headings, altitudes, flight profiles, turning rates, speeds, etc; probabilistic description of the time intervals between aircraft arrivals at the Basic Standard Approach Pattern (see item 3 above).
- 4.4 Outputs Obtainable: Traces of the paths of individual aircraft in the Basic Standard Approach Pattern; percentage of time each aircraft spends in close proximity with other aircraft; number of times when any two aircraft were within a prespecified distance of each other.
5. Computer-Related Characteristics: An aircraft and flight-track generating computer simulation program has been developed. No information is provided on computer language, computer running times, etc. A brief description of program logic (including some flow charts) is included.
6. Major Assumptions: Poisson arrivals in the terminal area; no traffic coordination or surveillance; all aircraft fly the same pattern (with some deviations from the intended flight paths) after entry into the terminal area; no consideration given to takeoffs or transient traffic.
7. Status of Model: The document reviewed in connection with this model is a "Phase I" report. The model as presented is far from completion, with several major questions left moot. It is not known to the reviewer, whether further progress has been made toward completing the model since the April 1975 date of the report.
8. Quality of Documentation: The quality of documentation is uneven. Some aspects of the model are discussed clearly and with mathematical elegance. Other aspects are described in a confusing and vague manner. The description of the simulation program is unsatisfactory.

9. Extent of Model Validation: It is indicated that the flight tracks generated by the model will be compared, for validation purposes, with related actual data collected by the NASA Wallops Flight Center, Wallops Island, Virginia.

10. Modularity and Flexibility: No judgement can be made in this regard, due to the fact that the simulation model described was still in development and major parts of it apparently had not been completed at the time when the referenced report was written.

11. Evaluation: This model is a long way from completion (at least in the version described by the referenced document). It is reviewed here because, at least conceptually, it offers an interesting alternative to the classical "gas model," which is the only one developed so far for uncontrolled traffic (see, for instance, "Terminal Air Traffic Model with Near Midair Collision and Midair Collision Comparison" by W. Graham and R. H. Orr, Appendix C-3 in Report of Department of Transportation Air Traffic Control Advisory Committee, December 1969). Rather than allow aircraft to fly "randomly" as in the gas model, the present analysis places them on a prespecified pattern and counts the number of close encounters between pairs of aircraft, assuming no pilot intervention.

It is very difficult to obtain some of the data required by this model, such as the amount of time a pilot in a VFR, terminal-area environment spends looking for other aircraft. However, this model can still be useful (provided it is developed further), in providing rough approximate measures of collision risk, just as the gas model does.



### MODEL C1.1

1. Primary Model Category: Noise-Related Models

2. Reports Used to Evaluate the Model:

- i) Title: FAA Integrated Noise Model - Version 1, Basic User's Guide

Authors: Anonymous

Agency: FAA, Office of Environmental Quality

Report #: FAA-EQ-78-01

Date: December 1977

- ii) Title: FAA Integrated Noise Model - Version 1, Computer Installation Instructions

Author: Anonymous

Agency: FAA, Office of Environmental Quality

Report #: FAA-EQ-78-03

Date: January 1978

3. Author's Abstract: The document contains a basic description of the application of the Integrated Noise Model, (INM), Version 1. The INM is a collection of computer programs which can be used to simulate aircraft operations at airports and display the noise contribution of those operations to the environment in the vicinity of the airport.

The INM consists of three nonconversational applications programs which are executed without any direct interaction with either the user or the operation system under which they are run. The three applications models are: The Grid Analysis Model, The Contour Analysis Model, and The Contour Plotting Package.

For acceptable definitions of aircraft operations, the model is capable of computing any or all of the following noise exposure measures: Noise Exposure Forecast (NEF), Equivalent Sound Level (Leq), Day Night Average Sound Level (Ldn), Community Noise Equivalent Level (CNEL), and Time Above a Threshold of A-weighted Sound Level (TA).

The document is designed to serve as a guide for the user,

management personnel, and the consultant. This guide will provide the means of applying the INM without the use of sophisticated forms or processes.

#### 4. Model Description:

4.1 Model Type: Analytical; deterministic

4.2 Factors of National Airspace System Related to Model: Relates traffic mix, traffic demand profiles and terminal area geometry to measures of noise exposure in the terminal area.

#### 4.3 Input Data Requirements:

Runways - Runways designation and geometry for up to 15 runways.

Tracks - up to 88 ground tracks can be defined for approach and departure paths. Each track can contain up to 15 curved or straight segments.

Profiles - aircraft altitude, velocity, and thrust must be specified at points along the ground track. For approach profiles, there is a standard internal data base for a given flap setting and landing weight which provides velocity and thrust settings for certain aircraft types. There can be up to 50 approach profiles. Departure profiles are internally generated given aircraft type and trip range for a standard ATA takeoff procedure. This can be modified to include a cutback segment which has an altitude restriction, a specified climb gradient, or a specified power (thrust) level.

Traffic Mix - expected number of operations by type, ground track, and profile, in a given period (day, evening (1700-2159), night (2200-0659)). There are currently 37 types of aircraft in an internal data base.

4.4 Outputs Obtainable: For a prespecified set of grid points around the runways, the output noise exposure data are average daily values for Leq, Ldn, NEF, CNEL. Also, data on TA (time above a threshold) values are given for 65, 75, 85, 95, 105, and 115 dbA levels

in minutes per day. For any grid point, a breakdown of the noise contribution can be provided under two options; (1) by "flight" (track, profile, and noise curve set number); and (2) by all the aircraft assigned to a given noise curve set.

For a map of the area around the runways, contour plots of any value of the noise exposure measures or the TA values can be made using a CALCOMP plotter.

5. Computer-Related Characteristics: The model is available through various computer services and consultants who are listed with the Office of Environment and Energy, FAA (AEE-100). Copies of the computer program and its data bases can be obtained from the same office. It is written in Fortran IV, and consists of 8300 lines of code. It requires approximately 90,000 bytes of core. Further details can be found in the second of the reports referenced in item 2.

6. Major Assumptions: Zero wind; surrounding topography is a flat, grassy plain; standard relative humidity; standard landing gross weights and flap settings; source noise strength varies only in azimuth, not in elevation.

7. Status of Model: The model is designed to satisfy the requirements of FAA Order 1050.1B (Vol. 42, No. 123, June 1977) for the noise analysis to accompany Environmental Impact Statements for changes in airport or ATC facilities or operations. It will be continuously updated, extended, and improved. Currently it is available as Version 1. Version 2 is scheduled for release in September 1979.

8. Quality of Documentation: There is a complete set of documentation for a new user. It is good, but there are a number of missing items and ambiguities. A clear, detailed explanation of the computational processes of the model does not seem to exist at this point.

9. Extent of Model Validation: A validation study is underway according to the Basic Users Guide.

10. Modularity and Flexibility: An extension of the model which



provides the user with the ability to work with the model in a conversational mode is presently being developed.

11. Evaluation: This model is now being tested to detect minor errors and to exercise all its options. The results of the validation study are needed to provide some idea of its accuracy in predicting community noise exposure levels. It is now the pre-eminent model, superseding all other models developed by the FAA, and various consultants, and will continue to be developed in future years. For the general user it provides a complete set of community noise exposure measures and their contours, which meet any need that might arise in studying proposed ATC changes in aircraft activity around the airport.

## MODEL C1.2

1. Primary Model Category: Noise-Related Models

2. Report Used to Evaluate the Model:

Title: Noise Prediction Technology for CTOL Aircraft

Author: John P. Raney

Agency: NASA Langley Research Center

Report: NASA Conference Publication 2036, Part II

Date: March 1978

3. Author's Abstract: The application of a new aircraft noise prediction program (ANOPP) to CTOL noise prediction is outlined. Noise prediction is based on semi-empirical methods for each of the propulsive system noise sources, such as the fan, the combustor, the turbine, and jet mixing, with noise-critical parameter values derived from the thermodynamic cycle of the engine. Comparisons of measured and predicted noise levels for existing CTOL aircraft indicate an acceptable level of accuracy.

4. Model Description:

4.1 Model Type: Analytical; deterministic

4.2 Factors of National Airspace System Related to Model: Relates aircraft aerodynamic characteristics, engine technology and flight path profile to noise impact of a flight.

4.3 Input Data Requirements: The model requires extensive technical data on aircraft aerodynamic performance and engine propulsion. A time history of thrust/weight, lift/drag, bank angle, flap setting, etc. is required to determine aircraft flight trajectory. For the engines, a T-S (temperature-entropy) diagram is either required or computed as a function of thrust and speed histories. Combustor inlet and exit pressures, total temperature rise across a fan, etc., are typical thermodynamic input data. The program contains a library of noise prediction modules which use these input data to calculate source noise for fan, compressor, jet, combustor, turbine, and airframe.

Atmospheric and ground attenuation factors, and directivity factors, are needed to compute the noise spectrum at a given observer point.

4.4 Outputs Obtainable: A time history of noise spectrum at a point on the ground is calculated for a flyover. From this, PNL and EPNL values are obtained.

5. Computer-Related Characteristics: Details of the computer program are not discussed in this report. It is described as having an efficient architecture, and a flexible data base management scheme to handle the large amount of data required by the noise prediction modules. A typical CTOL noise prediction analysis performed at the Langley Research Center is accomplished in a single run with a turn around time of two hours.

6. Major Assumptions: There are a number of rather technical assumptions involved in the methods used to calculate aircraft trajectories and the noise generation from individual components. They are not described in the report reviewed, but are discussed in the references listed in the report.

7. Status of the Model: The model is under continuing development at Langley Research Center to extend its capabilities and improve its methods of predicting component noise generation. It is currently used in the SCAR project (Supersonic Cruise Aircraft Research), and will be applied in other NASA aircraft research projects.

8. Quality of Documentation: The computer program does not appear to be documented, as it seems to be available only internally at present. The author does indicate that it would be available for preliminary design activity, presumably at aircraft manufacturers.

9. Extent of Model Validation: Validation studies have been carried out in different ways. Various tests and comparisons for noise generation by components have been made. Comparisons have been made between actual flyover data and model data for a Learjet, Concorde, and other aircraft. Further tests on wide-body transports



are planned. Good correlations in PNL, both as to noise strength and angular direction, are presented for the Learjet and Concorde with results generally within 2-3 dB.

10. Modularity and Flexibility: The computer program is described as modular. The selection of its outputs are controllable at execution time.

11. Evaluation: This model seems to afford a unique capability which ties together a diverse set of noise generation research activities so that aircraft flyover noise can be estimated during preliminary aircraft design. The initial results look extremely good. The existence of the model justifies further research to improve the methods of predicting noise generation from aircraft and engine components.

APPENDIX A  
GLOSSARY

Aircraft mix or traffic mix: the composition of the fleet of aircraft using a facility such as an airport, usually expressed in terms of the percentage of total traffic consisting of aircraft of each type.

Aircraft (performance) characteristics: the capabilities of an aircraft in flight or on the ground, including nominal cruising airspeed, nominal landing airspeed, nominal terminal area airspeed, maximum and nominal climb and descent rates, taxiing speed, runway acceleration or deceleration rates, etc.

Aircraft state: the instantaneous value of all data pertinent to an aircraft in flight, including the position vector, the velocity vector, the acceleration vector, pitch and bank angles, thrust, etc.

Airport operation: a landing or a takeoff.

ATC strategy: used in connection with terminal area operations, it implies the rules used for sequencing and scheduling operations on the runways and for determining the approach flight paths for landing aircraft. When a ground-based air traffic controller is responsible for the implementation of the strategy, the term ground control strategy is also used.

Event-paced simulation: a type of simulation in which the simulated time is advanced, not in regular intervals, but according to the instants when events of interest take place.

Final approach gate: the point on the final approach course which is one mile from the approach fix (outer marker) on the side away from the airport or five miles from the landing threshold, whichever is farther from the landing threshold.

Ground controller: the controller (or control position) responsible for control of aircraft on taxiways and aprons at airports.

Local controller: the controller (or control position) responsible for control of aircraft on runways and in the immediate vicinity of runways (in the air or on the ground).



Harp delay pattern: a set of terminal area flight paths leading into the final approach, which are bounded by a harp-like geometrical figure.

Lateness distribution: a probability distribution which is sometimes used to describe the amount of time by which the arrival of an aircraft at a particular point (usually the terminal area) deviates from its nominal arrival time.

Noise curve set: a set of noise curves, (noise level versus slant range) for different thrust settings. This set may be used to describe more than one type of aircraft.

Queue discipline: the set of rules used to determine the order in which those waiting in a queue will obtain access to the service for which they are waiting.

Runway service time: the length of time during which a runway is reserved exclusively for the use of one aircraft. The runway service time for landings or for takeoffs is usually greater than the runway occupancy times for these operations (and cannot be less than these occupancy times).

APPENDIX B  
BIBLIOGRAPHY

B-1/B-2

The primary model category (See Part I) associated with documents in the bibliography is indicated in brackets after each reference. Secondary categories, if any, are also indicated after a semicolon within the brackets.

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APPENDIX C  
REPORT OF NEW TECHNOLOGY

C-1/C-2

The work performed under this contract, while leading to no new invention, has provided air traffic control and airport specialists and planners with a useful guide of state-of-the-art models pertaining to the National Airspace System. The detailed model reviews in part III and comparative evaluations in part II should enable the selection of the most cost-effective model for each specific application.

275 copies

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